

Fuel consumption modeling in support of ATM environmental decision-making

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Abstract—The FAA has recently updated the airport terminal area fuel consumption methods used in its environmental models. These methods are based on fitting manufacturers' fuel consumption data to empirical equations. The new fuel consumption methods 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 these new methods can accurately capture the consequences of different terminal departure and arrival procedures on airplane fuel consumption within a reasonable level of uncertainty.

Keywords— *fuel consumption; emissions; environmental impacts*

I. INTRODUCTION

For decades, ways of reducing fuel consumption and its associated economic costs have concerned the aviation industry and the responsible government agencies. Reduction in fuel consumption will also lead to an overall reduction in greenhouse gas (GHG) emissions, and a reduction in engine exhaust pollutants of concern in local air quality studies.

One way of minimizing fuel consumption is through operational procedures such as Continuous Descent Arrivals (CDA) and Tailored Arrivals (TA). Determining the extent of the environmental and economic benefits of these operational procedures and others like them often relies on computer-based modeling. Currently available airplane performance models have been shown to have fuel consumption errors in the terminal area on the order of 20 to 40%, based on comparisons with airline Flight Data Recorder (FDR) information [1]. These errors are potentially large enough to lead to misguided policy decisions based on competing environmental and economic constraints.

A new method of calculating fuel consumption for aircraft operating in the terminal area was recently implemented [2]. The new method is based on using aircraft performance data from the manufacturer as input to a statistical program which calculates coefficients for empirical Thrust Specific Fuel Consumption (TSFC) models. The TSFC models are specific to either departure (high thrust conditions) or arrivals (low thrust). The new method was shown to be a significant improvement over existing fuel consumption models in the

terminal area, i.e. below 10,000 feet above field elevation (AFE).

This new terminal area fuel consumption method has been included in the Aviation Environmental Design Tool (AEDT), the U.S. Federal Aviation Administration's (FAA) next generation suite of integrated aviation environmental tools [3, 4]. No modifications have been made to AEDT cruise fuel consumption modeling as a result of this work.

II. BACKGROUND

Popular fuel consumption models used in aviation environmental analyses today are primarily based on either the International Civil Aviation Organization (ICAO) time-in-mode method [5] or EUROCONTROL's Base of Aircraft Data (BADA) [6].

ICAO time-in-mode method uses the certification fuel flow data from ICAO engine emission data sheets multiplied by a standard time for the Landing and Take-Off (LTO) cycle [7]. Recent work by Patterson [1] has shown that the ICAO time-in-mode method, which dates from when airplanes with three or four engines dominated the fleet, is not representative of current airline operations, which are dominated by twin-engine airplanes. Twin-engine airplanes have a higher thrust-to-weight ratio than three- or four-engine aircraft due to the safety requirement to climb with an engine inoperative. This higher thrust-to-weight ratio means the twin-engine aircraft have higher climb rates, rendering the ICAO certification LTO information obsolete for supporting accurate aircraft emission inventories.

The BADA fuel consumption model uses an energy-balance thrust model and TSFC modeled as a function of airspeed. BADA information on airplane performance and fuel consumption exists for a large part of the civil fleet. The BADA fuel consumption model has been shown to work well in cruise, with differences from airline reported fuel consumption of about 3%, as documented by Malwitz et al. [8] and Lee et al. [9]. However, comparisons of BADA-predicted and actual airline fuel consumption (reported via their FDR system) in the terminal area reveal that BADA does not perform as accurately in this region compared with cruise. An example of this is shown below in Figure 1. The figure compares fuel consumption data for one airline's fleet of Boeing 757-200 airplanes to both the prior BADA model and

the new (AEDT) model, which is discussed in more detail in the next section; the horizontal axis represents the total fuel consumed from the start of the takeoff roll up to 3,000 feet AFE as reported by the airplanes' FDR, and the vertical axis represents the modeled fuel consumption up to the same altitude. The open symbols represent the BADA method; the closed symbols represent the new method, as implemented in AEDT. Each data point represents a comparison of the fuel consumption for one flight's departure from the start of the takeoff roll up to 3,000 feet AFE. The fuel consumption data for both models were generated with the airline's reported airplane weight as well as the airport elevation and the temperature at the time of takeoff. Note that the thrust for both methods was calculated using the methods described in SAE-AIR-1845 [10] and ECAC Doc. 29 [11], as implemented in the FAA's AEDT. For the operations in Figure 1, the average difference between the fuel consumption reported by the airplanes' FDR and the BADA model is -21.5% (the negative number indicates an under-prediction), while the average difference for the AEDT model is +1.5% (the positive number indicates an over-prediction).

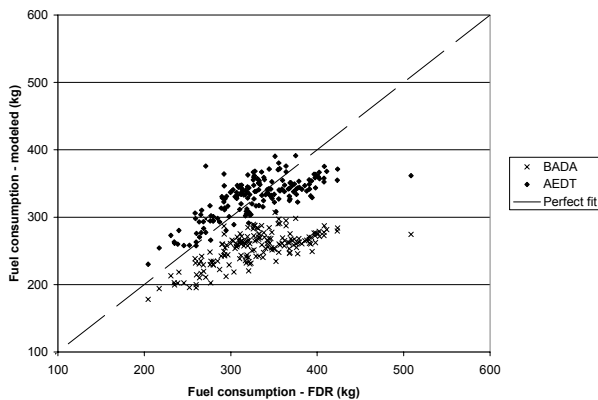


Figure 1: Comparison of fuel consumption methods for 757-200 departures to 3,000 feet AFE

The data shown in Figure 1 include the effects of air traffic management (ATM) procedures – note that one point has an FDR fuel consumption of over 500 kg, but a BADA-computed fuel consumption of less than 300 kg; the corresponding AEDT data point is less than 400kg. These points represent a flight which experienced an ATM ‘hold-down’ – a climb restriction while the airplane was still below 3,000 feet AFE. Modeled fuel consumption does not well represent this type of operational anomaly – the models assume all airplanes depart using standard procedures, which in AEDT are the ICAO B departure procedures [12]. While the models do not capture these ATM-influenced operational anomalies, these happen infrequently below 3,000 feet AFE and so will not significantly influence the aggregated fuel consumption of a broader fleet inventory.

Figure 1 also contains a diagonal line labeled ‘perfect fit.’ If the modeled data matched the FDR system data exactly, all the data points would lie on this line. We include the ‘perfect fit’ line in this and the following figures to assist the reader’s

ability to judge the relative quality of the modeled fuel consumption.

III. AEDT TERMINAL AREA FUEL CONSUMPTION MODEL

Given that the intent of BADA is to model airplane performance and fuel consumption in cruise mode and that BADA has been optimized to do so, the comparison presented in Figure 1 is not a surprise. However, the differences between the BADA modeled and the FDR fuel consumption illustrate the need for an improved method in the terminal area. The 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.

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

The arrival TSFC equation below (2) is based on work by Hill [13] with modifications by Yoder [14].

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

In the equations above, θ is the temperature ratio, M is the aircraft Mach number, h_{MSL} is the height of the aircraft above Mean Seal Level, F is the thrust of the engine, δ is the pressure ratio, and F_0 is the maximum thrust at Sea Level static conditions. For each equation, 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.

The required airplane performance data can be generated by a computer-based tool. Such tools are available internally at most major airframe manufacturers. For this work, we used the Boeing Climbout Program (BCOP), which engineers from Boeing made available through a cooperative agreement between the U.S. FAA and the Boeing Company.

A statistical analysis software package was used to determine the coefficients from the collected flight database. For this work, the coefficients were generated using linear and non-linear analysis tools, based on minimizing the least-squared error between the TSFC calculated from the BCOP data and the TSFC found from departure and arrival TSFC equations given above.

IV. VALIDATION OF THE NEW METHOD WITH FDR INFORMATION

Validation of the new fuel consumption method was conducted by comparing in-service airline fuel consumption data to the fuel consumption predicted by these new methods. The airline fuel consumption data are part of FDR data sets collected from a number of airlines. Some of these FDR data sets include second-by-second records from engine start-up at the departure gate to engine shut-down at the arrival gate. Other airlines have provided aggregated fuel consumption data; these aggregated data allow validation of the method up to particular altitudes, but provide no detailed flight data.

A. Departure Operations

An example comparison of the new fuel consumption method and the FDR reported fuel consumption is given below in Figure 2. The data points represent fuel consumption modeled by the proposed method as implemented in AEDT for the same airplane and airport initial conditions as reported in the in the FDR data set. The data represented in Figure 2 are for the 757-200, as in Figure 1, but are from a different airline operating at different airports from those represented in Figure 1. In the case of the airline in Figure 2, the data clearly divide into two clusters; one cluster where the new method significantly over-predicts the fuel consumption (the data cluster which lies above the perfect fit line, with an average difference of +12.1%), and a second cluster where the new method more accurately predicts the fuel consumption (the data cluster around the perfect fit line, with an average difference of -4.1%). A detailed look at these data showed that the cluster with the higher fuel consumption prediction was dominated by flights originating in Europe, while few European-origin flights were represented in the second, more accurate cluster. This observation prompted a discussion with the airline on their operational procedures (the FDR data from this airline was presented in aggregate form, so the details of individual flight procedures could not be determined). This airline uses a considerably different departure procedure for their European operations compared to their domestic U.S. operations. Their domestic U.S. procedure calls for the pilots to accelerate and retract the flaps after reaching 1,500 feet AFE. Their European procedure calls for the pilots to maintain takeoff flaps until reaching 3,000 feet, then accelerate to flap retraction speed. The European procedure of maintaining the takeoff flap setting means a quicker climb to 3,000 feet, but the aircraft will have less airspeed when reaching this altitude. Note that this European procedure is similar to an ICAO A departure. The modeling done in Figure 2 assumed all flights used the U.S. domestic procedure.

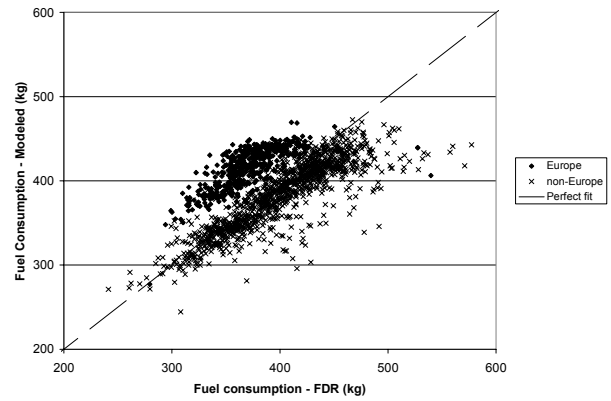


Figure 2: Fuel consumption for 757-200 departure to 3,000 feet AFE

Re-analyzing the data taking into account this airline’s European departure procedure, which maintains take-off flaps up to 3000 feet, the modeled fuel consumption returns to clustering around the perfect fit line, as shown in Figure 3, which presents the data for the European flights only. The average difference between the FDR and the modeled data for the operations in Figure 3 is +1.2%. We note that this airline’s European take-off procedure consumes less fuel to 3,000 feet, but this does not mean that procedure consumes less fuel for the entire flight – the lower fuel consumption is correlated with the lower airspeed at 3,000 feet; airplanes with this lower airspeed require a greater acceleration at some point in the climb to cruise, negating the fuel saving in the initial climb.

We draw two conclusions from this example. The first is that details of a procedure have a direct influence on the accuracy of the modeling when an analysis is restricted to a particular segment of the entire flight. Second, the new methods accurately model the fuel consumption when the procedures themselves are accurately modeled.

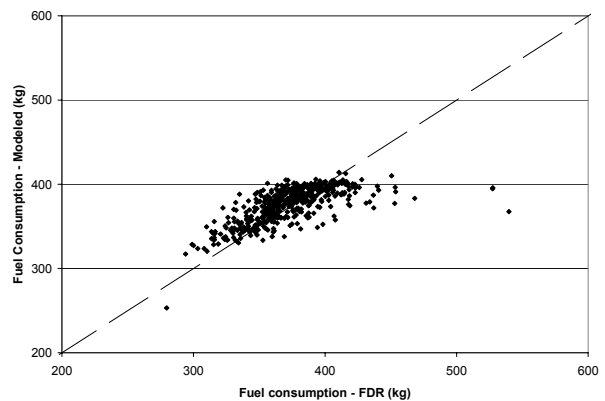


Figure 3: Fuel consumption for 757-200 to 3,000 feet AFE, European flights modeled with correct procedure

The previous examples have all been for flight segments below 3,000 feet AFE. Figure 4 below shows the results of fuel consumption modeling for a limited set of 747-400 data from the start of the take-off roll up to 10,000 feet AFE. In this case, the data tend to cluster along the perfect fit line; the cluster with the lower fuel consumption (2,000 to 2,500 kg) represents intra-Asian flights, the cluster with the higher fuel consumption

(3,000 to 3,500 kg) represents trans-Pacific operations. The trans-Pacific operations have significantly higher take-off weights than the intra-Asian flights and so require more fuel to reach a given altitude. At these higher altitudes, modeled fuel consumption tends to under-predict the reported fuel consumption. This happens because the modeled flights do not capture all the details of the actual flights; the deviations of the actual flight from the standard departure procedures used in the model tend to increase the fuel consumption. The average difference between the FDR and the modeled data for the operations in Figure 4 is -7.9%.

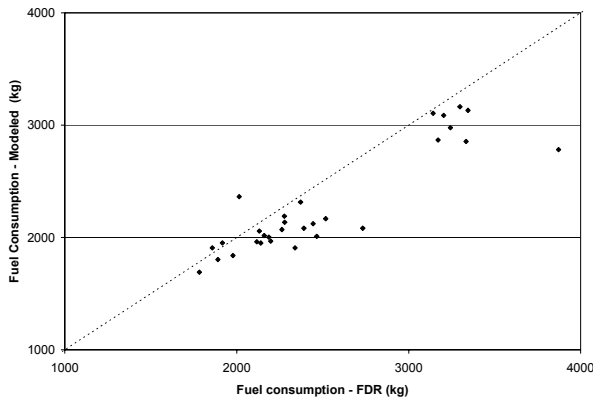


Figure 4: Fuel consumption for 747-400 departure to 10,000 feet AFE

Figure 5 below shows the departure profile for the flight in Figure 4 which has the highest FDR fuel consumption up to 10,000 AFE (the point with an FDR fuel consumption a little less than 4,000 kg). This flight experienced two altitude holds: one at 6,000 feet MSL and another at 9,000 feet MSL. These altitude holds are not captured in the modeled fuel consumption – the model assumes an uninterrupted departure to 10,000 feet MSL. Note that the fuel consumption penalty for the altitude holds is actually less than the difference between the modeled and the FDR fuel consumption; during the altitude holds, the aircraft may still be moving towards the destination airport, so the fuel consumed in the altitude holds is not entirely wasted.

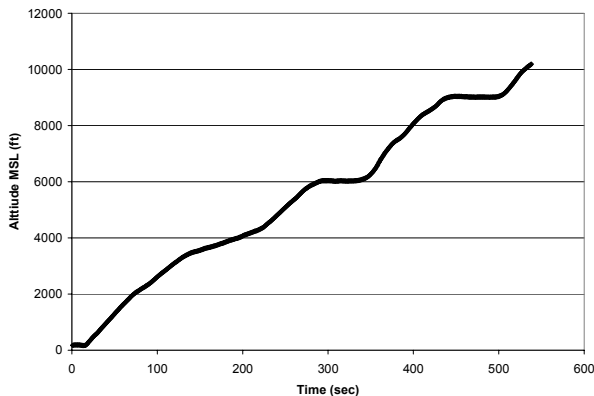


Figure 5: Departure profile for 747-400 with the highest fuel consumption in Figure 4

The 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

The companion figure to Figure 1 for fuel consumption during arrival operations is shown below in Figure 6. As before, the horizontal axis represents the fuel consumption as reported by the FDR system and the vertical axis represents the modeled fuel consumption computed using the method presented herein. In this case, the influence of ATM procedures is removed from the analysis by taking the thrust and airplane state variables from the FDR system data, rather than from FAA’s AEDT performance model. If an airplane is given a step-down arrival procedure, the associated thrusts and speeds are used in the TSFC model, rather than the thrusts and speeds of a generic arrival procedure, as would be found in AEDT. This was done because the arrival fuel consumption is dependent on airplane parameters which have relatively more variation than they do during departure: during an arrival the thrust of the engines can range from several thousand pounds (required during a level segment) to negative values (when the ram drag on the fan is greater than the thrust). The average difference between the FDR and the modeled fuel consumption data for the operations in Figure 6 is +1.5%.

As with the departure operations, similar results were obtained for different airplane arrivals from 10,000 AFE.

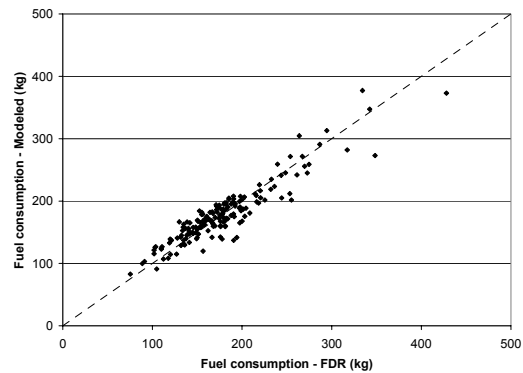


Figure 6: Fuel consumption for 757-200 arrival from 3,000 feet AFE

V. CONCLUSIONS

This paper presents the results of using a new method of computing terminal area airplane fuel consumption that has been implemented in FAA’s AEDT. The new method shows sufficient fidelity to enable modelers to accurately capture the effects of operational changes on airplane fuel consumption such as Continuous Descent Arrivals, Tailored Arrivals, and reduced-powered takeoffs. This improvement in fuel consumption modeling will be important as policy makers seek to improve the efficiency of the national and international airspace system while considering the associated environmental impacts, an important objective of the FAA’s Next Generation Air Transportation System (NextGen) and of EUROCONTROL’s Single European Sky ATM Research (SESAR) initiative.

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