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Modeling of Terminal-Area Airplane Fuel Consumption

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Accurate modeling of airplane fuel consumption is necessary for air transportation policy-makers to properly adjudicate trades between competing environmental and economic demands. Existing public models used for computing terminal-area airplane fuel consumption have been shown to have substantial errors, potentially leading to erroneous policy and investment decisions. The method of modeling fuel consumption proposed in this paper was developed using data from a major airplane manufacturer. When compared with airline performance/operational data, this proposed method has been shown to accurately predict fuel consumption in the terminal area. The proposed method uses airplane performance data from publicly available environmental models supported by the Federal Aviation Administration and others. The proposed method has sufficient generality to protect the proprietary interests of the manufacturer, while still having adequate fidelity to analyze low-speed airplane operations in the terminal area. This improved methodology will enable more informed decisions by policy-makers seeking to account for the effects of fuel consumption and airplane emissions on plans for future airspace and airport designs.

Nomenclature

Fo = static thrust at sea level standard conditions
F/δ = net corrected thrust
h_{MSL} = height above mean sea level
K_1 = departure thrust specific fuel consumption constant coefficient
K_2 = departure thrust specific fuel consumption Mach number coefficient
K_3 = departure thrust specific fuel consumption altitude coefficient
K_4 = departure thrust specific fuel consumption thrust coefficient
M = Mach number
α = arrival thrust specific fuel consumption constant coefficient
β_1 = arrival thrust specific fuel consumption Mach number coefficient
β_2 = arrival thrust specific fuel consumption thrust term coefficient
β_3 = arrival thrust specific fuel consumption thrust coefficient
δ = pressure ratio
θ = temperature ratio

I. Introduction

FUEL consumption and its economic costs have been a concern of the aviation industry for decades. Fuel currently constitutes airlines' largest fraction of operating costs [1]. Airlines, regulatory organizations, and airplane manufacturers are seeking ways to reduce fuel consumption and minimize the resultant economic impact on the airlines. This will also lead to an overall reduction in greenhouse gas emissions associated with fuel consumption and a reduction in those engine exhaust pollutants that can cause illness and premature mortality [2].

One way of minimizing fuel consumption is through operational procedures such as continuous descent arrivals and tailored arrivals. 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 [3]. These errors are potentially large enough to lead to improper policy decisions based on competing environmental and economic constraints.

This paper discusses an improved method of modeling terminal-area airplane fuel consumption that leads to smaller differences between modeled and measured fuel consumption. The method is based on using airplane manufacturers' existing airplane performance tools to generate statistically derived coefficients for separate thrust specific fuel consumption (TSFC) equations in the departure and arrival phases of flight below 10,000 ft above field elevation (AFE); this method is not a modification of the existing cruise fuel consumption methods discussed subsequently. This method is planned for inclusion in the Federal Aviation Administration's (FAA's) next-generation suite of integrated aviation environmental tools: the Aviation Environmental Design Tool (AEDT).§

II. Existing Fuel Consumption Models

In times of rising fuel costs, aviation stakeholders have worked to develop improved algorithms for modeling fuel consumption. In the last period of significant fuel cost increases, the early 1980s, researchers sought to improve measurements of airline fuel efficiency through more accurate modeling of fuel consumption, as exemplified by the work of Collins [4]. More recently, Trani et al. [5] have investigated the use of neural networks to estimate fuel consumption. These models gained limited acceptance, perhaps because of their requirements for either detailed airplane aerodynamic

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§Data available online at http://www.faa.gov/about/office_org/headquarters_offices/aep/models/ [retrieved 16 April 2009].

information or a large database of airplane operations and associated airplane state data.

The existing fuel consumption models that have gained wide use in environmental analyses are primarily based on either the International Civil Aviation Organization (ICAO) reference emissions landing and takeoff (LTO) cycle method [6] or EUROCONTROL's base of aircraft data (BADA) [7].

ICAO time-in-mode methods use the fuel flow data from ICAO engine-emission data sheets multiplied by a standard time for the LTO cycle [8]. Recent work by Patterson et al. [3] has shown that the ICAO time-in-mode method is not representative of real-world airline operations.

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. [9] and Lee et al. [10]. However, comparisons of BADA and 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 in Fig. 1: the horizontal axis represents the total fuel consumed from the start of the takeoff roll up to 3000 ft AFE for one airline's fleet of Boeing 757-200s, and the vertical axis represents the BADA-modeled fuel consumption. Each data point represents the fuel consumption for one departure. The BADA-modeled fuel consumption data were generated with the airline's reported airplane weight as well as the airport elevation and the temperature at the time of takeoff. Note hat for the terminal area, the thrust for the BADA method was calculated using the methods described in [11,12], as implemented in a prototype of the FAA's AEDT (see footnote [§]). For the departures in Fig. 1, the average difference between the BADA-modeled fuel consumption and the airline's reported fuel consumption to 3000 ft was −73.3 kg (the negative number indicates that the model underpredicted the fuel burn) or −22.3% of the fuel consumed. The standard deviation of the difference in fuel consumption was 35.8 kg.

The data shown in Fig. 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. This point represents a flight that experienced an ATM hold-down: a climb restriction while the airplane was still below 3000 ft AFE. Modeled fuel consumption does not represent this type of operational anomaly; the model assumes all airplanes depart using standard procedures. The model does not capture these ATM-influenced operational anomalies, but below 3000 ft AFE, these anomalies happen infrequently and should not significantly influence the aggregated fuel consumption of a broader fleet inventory.

Figure 1 also contains a diagonal line labeled *Perfect fit*. If the BADA-modeled data matched the FDR system data exactly, all the data points would lie on this line. We included the perfect-fit line in this and the following figures to ease the reader's ability to judge the relative quality of the modeled fuel consumption.

III. Proposed TSFC 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 Fig. 1 is not a surprise. However, the differences between the modeled and the FDR fuel consumption show the need for an improved method in the terminal area. The new fuel consumption method needs to be more accurate than existing methods, easy for manufacturers to supply requisite data while protecting their proprietary interests, compatible with existing and planned environmental models, and needs to provide a level of accuracy that enables decision-makers to have confidence in modeled results (approximately ±5% target accuracy, when compared with measured data). Examination of the fuel consumption characteristics of turbofan engines led to the conclusion that a single algorithm would not suffice to cover the requirements of both departures and arrivals. Examples of turbofan fuel consumption characteristic plots are given by Corning [13]. These TSFC plots indicate little or no dependence on thrust in the departure mode of high power and low Mach number, whereas for the low-thrust and medium-to-low Mach numbers typical of arrivals, the TSFC has a nonlinear dependence on thrust.

A. Algorithms

One of the important considerations for a TSFC algorithm is the type of thrust model with which the TSFC algorithm will be used; the TSFC algorithm should be on the same order of precision and accuracy as the associated thrust model. For current environmental models, the thrust in the terminal area is determined using the method described in [11] and as enhanced in [12]. This thrust model uses a linear relationship on velocity and a quadratic relationship on altitude to predict thrust in two departure thrust modes: rated takeoff power and maximum climb power.

The TFSC plots from all major engine manufacturers are presented as functions of Mach, thrust, and altitude. The proposed departure TSFC algorithm uses linear relationships for these pa-

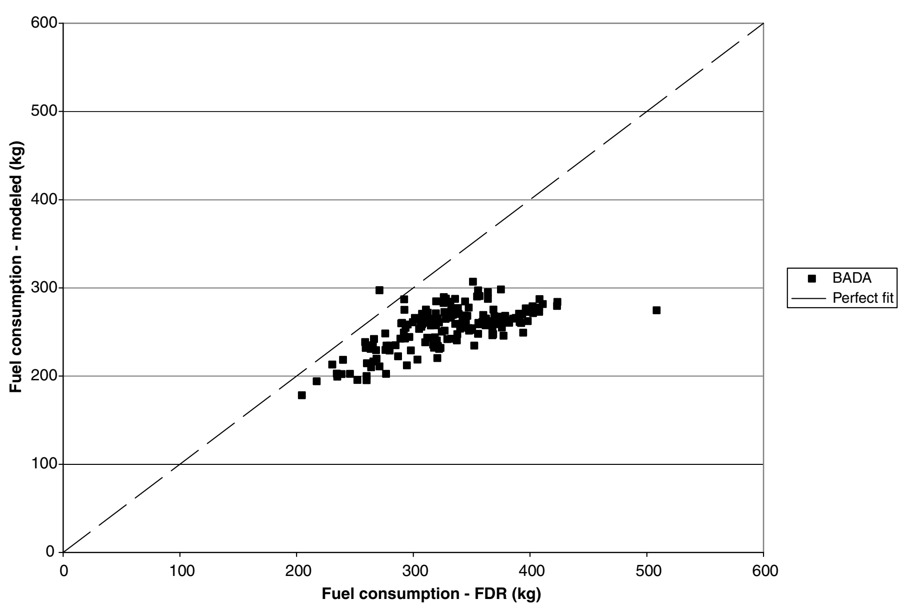

Fig. 1 Comparison of FDR and BADA-modeled fuel consumption for Boeing 757-200 departures to 3000 ft AFE.

rameters, with the addition of a dependence on the square root of the temperature ratio θ, based on a dimensional analysis as given by Hill and Petersen [14]. The proposed departure TSFC algorithm is given in Eq. (1); the coefficients K_i are determined for individual airplane types, as discussed subsequently:

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

The proposed arrival TSFC algorithm is based on Hill and Petersen [14], with modifications by Yoder [15]. The Yoder implementation of fuel consumption has been further simplified; sensitivity tests showed that the proposed arrival TSFC algorithm given in Eq. (2) accurately represents arrival fuel consumption in the terminal area:

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

As with the departure TSFC equation, the determination of the individual arrival coefficients α and β_i are discussed subsequently.

B. Tools and Methods

Determining the fuel consumption coefficients for a particular airframe/engine combination is based on the process of generating airplane performance data for the expected range of terminal-area operations, collecting those data into a common structure, and then statistically analyzing those data. Neither the tools nor the methods described herein are mandatory for the generation of the coefficients; a different source of fuel consumption data, such as from a different manufacturer's airplane performance program, could be used. The only requirement is that the fuel consumption data be of precision comparable with the aerodynamic performance model to which they are coupled.

The airplane performance data can be generated by a computer-based airplane performance tool. The tool used in support of this paper is a terminal-area performance calculator developed by The Boeing Company. This calculator, the Boeing Climb-Out Program (BCOP), collects required input data, such as airport temperature, elevation, and runway information, and combines that data with initial airplane state information, such as takeoff weight, profile data, and flap retraction schedules, to determine airplane state parameters as a function of time and distance during the terminal operation. Boeing engineers developed BCOP for the primary purpose of assisting airlines with determining airplane engine-out performance during either departure or arrival operations.

BCOP's outputs for a range of different airplane weights, flight conditions, and airport operational conditions were collected into a flight database. The range of these collected parameters captured the limits expected in practice: the airplane weights ranged from those used to fly a minimum trip distance of 500 n mile to the maximum takeoff weight, different flap configurations were used, and the airport elevations ranged from sea level to 6000 ft mean sea level (MSL). For arrivals, the speed was varied from the maximum allowed in terminal airspace (250 kt) to the minimum flight speed with the airplane in landing configuration. This matrix of different weights and operational conditions, each of which represents a separate BCOP run with hundreds of time-step data records, yielded several thousand data records for each airplane's flight database.

A statistical analysis software package was used to determine the coefficients from the flight database. The coefficients in this study were generated by using Statistica's [16] linear and nonlinear analysis modules, based on minimizing the least-squares error between the TSFC calculated from the BCOP data and the TSFC found from Eqs. (1) and (2) given previously. An example of the relationship between Mach number, thrust, and TSFC at sea level found with this method for arrival conditions is shown in Fig. 2.

IV. Results of Comparison of Models with FDR Information

The fuel consumption coefficients generated using the preceding process were tested against a set of actual fuel consumption data for airplanes in airline service. The airline fuel consumption data are part of FDR data sets collected from a number of airlines from engine startup at the departure gate to engine shutdown at the arrival gate. The authors consider these FDR data to be the best available information on in-service airline fuel consumption.

In the examples given subsequently, the measured fuel consumption data are from the FDR and are given on the horizontal axis; the modeled fuel consumption data on the vertical axis are calculated from the improved fuel consumption methods discussed in this paper, as implemented in FAA's AEDT.

A. Departure Operations

An example comparison of the new fuel consumption method and the FDR-reported fuel consumption is given in Fig. 3. 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. For the departures in Fig. 3, the average difference between each flight's AEDT-modeled fuel consumption and the reported fuel consumption to 3000 ft was 1.4 kg, or 0.4% of the fuel consumed. The standard deviation of the

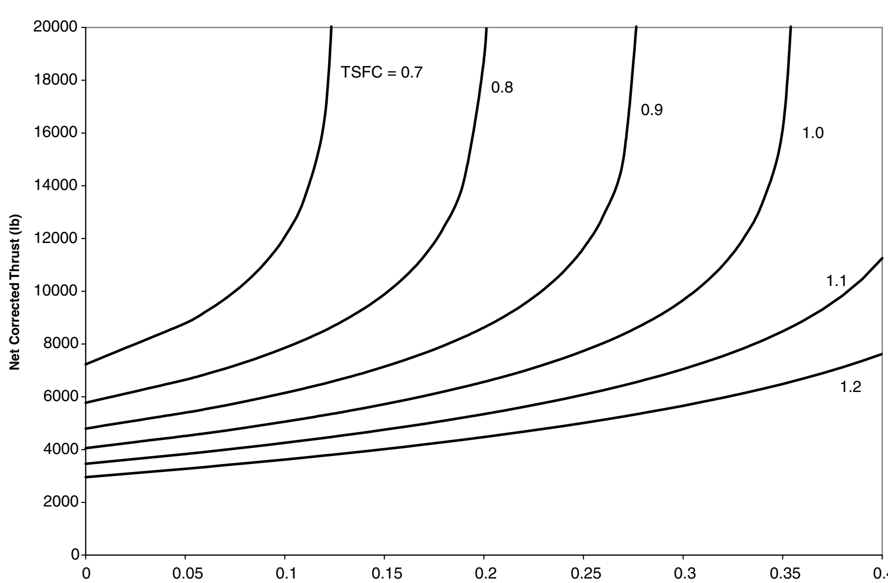

Fig. 2 Example arrival TSFC curves generated with Eq. (2).

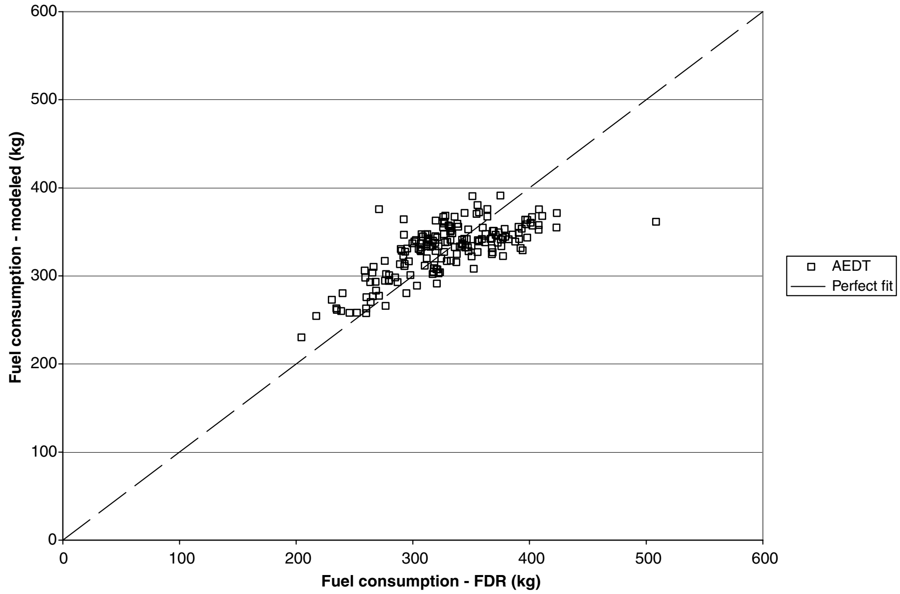

Fig. 3 Comparison of FDR and AEDT-modeled fuel consumption for Boeing 757-200 departures to 3000 ft AFE.

difference in AEDT-modeled and the reported fuel consumption was 32.3 kg. Results generated for the 767-300 and the 777-300ER are similar to those presented here for the 757-200.

In addition to the fuel consumption to 3000 ft AFE shown previously, Fig. 4 presents the aggregate fuel consumption to 10,000 ft AFE for the data set of 777-300ER flights. These data are of the same order of accuracy and precision as the 757-200 data up to 3000 ft AFE, with a few data points again representing ATM-influenced operational anomalies. For the departures in Fig. 4, the average difference between each flight's AEDT-modeled fuel consumption and the reported fuel consumption to 10,000 ft was 85.6 kg, or 4.8% of the fuel consumed. The standard deviation of the difference in AEDT-modeled and the reported fuel consumption was 85.6 kg. The TSFC coefficients were developed with an expectation that 10,000 AFE would be the limit of their applicability; above this altitude, we expect the algorithms to lose accuracy.

B. Arrival Operations

The companion figure for fuel consumption during arrival operations is shown in Fig. 5. 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). For these arrivals, the average difference between each flight's AEDT-modeled fuel consumption and the reported fuel consumption from 3000 ft was −0.6 kg, or −0.3% of the fuel consumed. The standard deviation of the difference in AEDT-modeled and the reported fuel consumption was 18.8 kg.

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

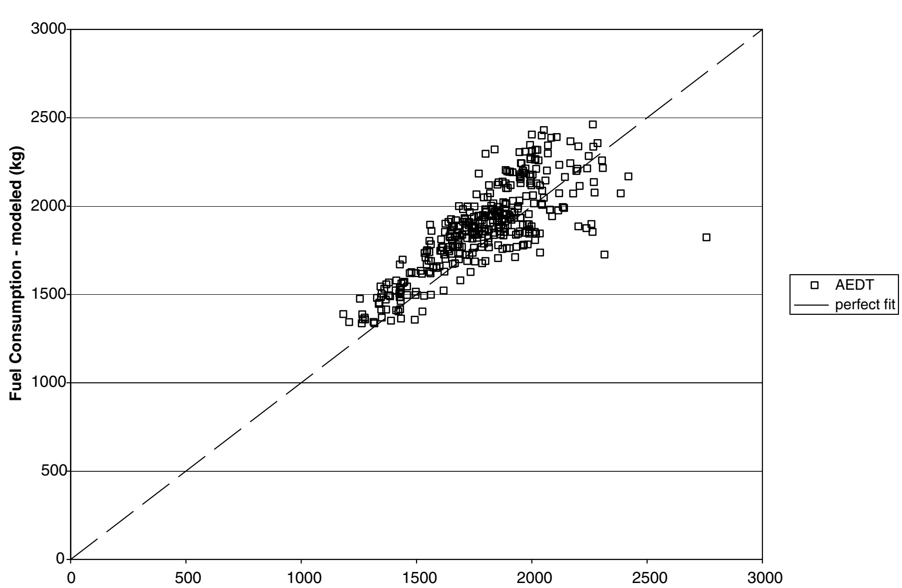

Fig. 4 Comparison of FDR and AEDT-modeled fuel consumption for Boeing 777-300ER departures to 10,000 ft AFE.

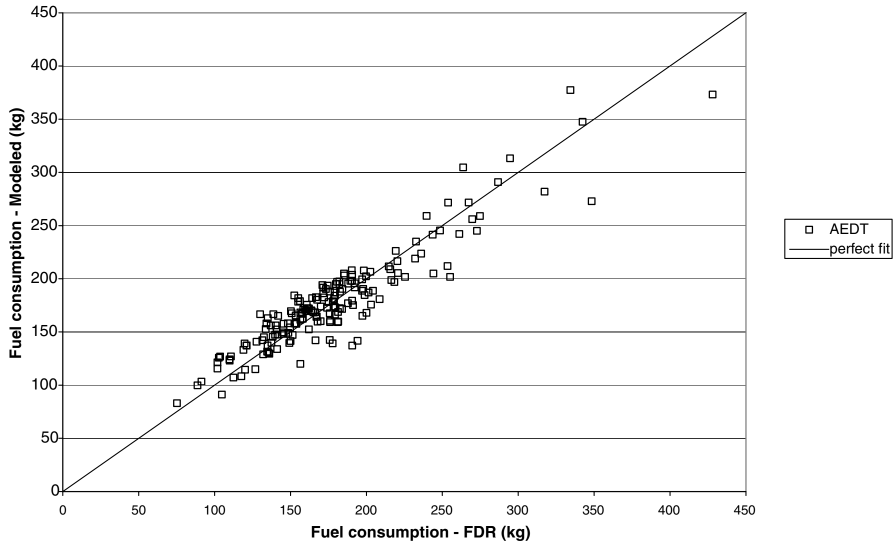

Fig. 5 Comparison of FDR and AEDT-modeled fuel consumption for Boeing 757-200 arrivals from 3000 ft AFE.

V. Conclusions

This paper presents an improved method of computing terminal-area airplane fuel consumption that is fully compatible with existing aviation environmental impact models such as the FAA's AEDT and that is easy for manufacturers to supply requisite data while protecting their proprietary interests. Based on comparisons with airline FDR data, the proposed method has accuracy of $\pm 5\%$ or better up to 10,000 ft AFE.

The method can be used to improve the accuracy of terminal-area ATM studies in which environmental considerations are a factor. Such studies include continuous descent arrivals, tailored arrivals, and preferred routings. These studies will be important as policy-makers seek to improve the efficiency of the national airspace system while considering the associated environmental impacts, an important objective of the Next Generation Air Transportation System (NextGen).

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