

Procedures for the Calculation of Airplane Fuel Consumption

RATIONALE

This SAE Aerospace Information Report (AIR) provides aviation environmental modelers with standard procedures for calculating the fuel consumption of airplanes in all phases of flight. The methods contained in this AIR make use of airplane performance models, such as found in AIR1845 or Eurocontrol's BADA 3. The fuel consumption predicted by these methods can be used as inputs to emission calculations, such as found in AIR5715.

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1. SCOPE

This SAE Aerospace Information Report (AIR) describes procedures for calculating fuel consumption for civil jet airplanes through all modes of operation for all segments of a flight. Turboprop and piston airplanes, as well as helicopters or unconventional aircraft, are not included in this AIR. The principle purpose of these procedures is to assist model developers in calculating airplane fuel consumption in a consistent and accurate manner that can be used to address various environmental assessments including those related to policy decisions and regulatory requirements. This AIR is intended to directly support the emission calculations documented in AIR5715. The models described in this AIR are intended to be used from the start of the takeoff roll to the end of the ground roll; taxi fuel consumption models are not included. If modelers have access to higher fidelity methods, they should use those methods in lieu of the ones in this AIR.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR1845 Procedure for the Calculation of Airplane Noise in the Vicinity of Airports

AIR5715 Procedure for the Calculation of Aircraft Emissions

DuBois, D. and Paynter, G., "Fuel Flow Method2' for Estimating Aircraft Emissions," SAE Technical Paper 2006-01-1987, 2006, <https://doi.org/10.4271/2006-01-1987>.

2.1.2 AIAA Publications

Available from American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344, Tel: 703-264-7500, www.aiaa.org.

Patterson, J., Noel, G.J., Senzig, D.A., et al., "Analysis of Departure and Arrival Profiles Using Real-Time Aircraft Data," J. of Aircraft, Vol. 46, No. 4, 2009.

Senzig, D.A., Fleming, G.G., and Iovinelli, R.J., "Modeling of Terminal-Area Airplane Fuel Consumption," J. of Aircraft, Vol. 46, No. 4, 2009.

2.1.3 ICAO Publications

Available from International Civil Aviation Organization, 999 University Street, Montreal, Quebec H3C 5H7, Canada, Tel: +1 514-954-8219, <http://www.icao.int/>.

ICAO, "International Standards and Recommended Practices," Environmental Protection, Annex 16, Vol. 2 - Aircraft Engine Emissions, 3rd ed., Montreal, July 2008.

ICAO, "Recommended Method for Computing Noise Contours around Airports," Doc. 9911, 2008.

[ICAO Aircraft Engine Emissions Databank | EASA \(europa.eu\)](https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank) (<https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank>), retrieved May 2022.

2.1.4 Other Publications

European Civil Aviation Conference, "Report on Standard Method of Computing Noise Contours around Civil Airports," Doc. 29, December 2016.

EUROCONTROL Experimental Centre (EEC), "User Manual for the Case of Aircraft Data (BADA), Revision 3.15," EEC Technical/Scientific Report No. 19/03/18-45, May 2019.

EUROCONTROL Experimental Centre (EEC), "Aircraft Noise and Performance (ANP) Database," ([ANP - Eurocontrol Experimental Centre \(aircraftnoisemodel.org\)](https://www.aircraftnoisemodel.org) (<https://www.aircraftnoisemodel.org>), retrieved May 2022.

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 Code of Federal Regulations (CFR) Publications

Available from the United States Government Printing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-1800, www.gpo.gov.

40 CFR Part 87 Control of Air Pollution from Aircraft and Aircraft Engines

2.2.2 Other Publications

Press, W.H., et al. "Numerical Recipes in Fortran 77, The Art of Scientific Computing, 2nd Edition," Cambridge University Press, 1992; (s3.amazonaws.com/nrbook.com/book_F210.html), retrieved May 2022.

U.S. Department of Transportation, "Use of Third-Party Aircraft Performance Tools in the Development of the Aviation Environmental Design Tool (AEDT)," DOT-VNTSC-FAA-11-08, 2011.

U.S. Environmental Protection Agency, "Control of Air Pollution from Aircraft and Aircraft Engines, Proposed Standard," Federal Register, Vol 37, No. 239, p 26488, December 12, 1972.

U.S. Environmental Protection Agency, "Control of Air Pollution from Aircraft and Aircraft Engines; Emission Standards and Test Procedures," Federal Register, Vol 47, No. 251, p 58462, December 30, 1982.

2.3 Definitions

JET A: The primary turbofan engine fuel. Jet A has a energy density of about 43 MJ/kg. This AIR assumes the use of Jet A fuel.

THRUST SPECIFIC FUEL CONSUMPTION: The ratio of the fuel mass flow to the net thrust of a turbojet or turbofan engine.

2.4 Abbreviations

AFE	Above Field Elevation
AIAA	American Institute of Aeronautics and Astronautics
ANP	Aircraft Noise and Performance database
ECAC	European Civil Aviation Conference
ECS	Environmental Control System
FDR	Flight Data Recorder
ICAO	International Civil Aviation Organization

LTO	Landing and Take-off cycle
MSL	Mean Sea Level
N1	Turbofan engine outer spool rotational rate
TSFC	Thrust Specific Fuel Consumption

3. INTRODUCTION

Airplane fuel consumption is an important environmental effect of aviation. Fuel consumption from aviation operations, important for its environmental and economic effects, also directly affects the generation of CO₂ and other emissions. The ability to accurately model the fuel consumption of airplane operations is a concern for governments, commercial operators, airports, and private citizens and organizations.

This AIR focuses on modeling the fuel consumption of airplanes with turbojet and turbofan engines. This AIR assumes that underlying airplane performance and atmospheric models are available to the modelers from other methods or standards.

This AIR includes information that enables aviation environmental modelers to estimate the fuel consumption from jet airplane operations in a variety of flight regions. The current state-of-the-art requires separate fuel consumption models for different flight regions. These models and their regions of applicability are discussed in Section 4 (terminal area models) and Section 5 (en-route models).

4. TERMINAL AREA FUEL CONSUMPTION MODELS

The following sections discuss three methods of determining fuel consumption in the terminal area (i.e., near the airport, generally lower than 10000 feet MSL). The sections are tiered such that the lowest fidelity model (4.1) is presented first, and the highest fidelity model (4.3) presented last. The basis for choosing one method over another depends on the modeler's need to balance accuracy and resources (including data availability).

4.1 Landing and Take-Off (LTO) Cycle Time-in-Mode Model

The LTO cycle time-in-mode is the ICAO reference method. The method dates from the early 1970s (EPA, 1972). The fuel consumption rates during the different modes of the LTO cycle are multiplied by the associated standard time-in-mode. The times-in-mode for the airborne parts of the LTO are assumed to occur between the airport surface and 3000 feet AFE. Table 1 presents the percent of the rated power output and the times in mode used in the four different LTO modes. Patterson et al. (2009) have shown that the ICAO LTO method generally over-predicts fuel consumption for airplanes in current practice.

Table 1 - LTO modes

LTO Mode	Power (Percent of Rated Output)	Time in Mode (Minutes)
Take-off	100%	0.7
Climb-out	85%	2.2
Approach	30%	4.0
Idle	7%	26.0

4.2 Boeing Fuel Flow Method 2

This fuel consumption method is part of Boeing Fuel Flow Method 2 (BFFM2) (DuBois, 2006), which documents a method of determining the emissions of airplanes from their fuel consumption.

4.2.1 General Model

$$f_n = \frac{BR_0 \delta}{\theta^{3.8} e^{0.2M^2}} \quad (\text{Eq. 1})$$

where:

B = mode-specific constant (dimensionless)

R_0 = static condition fuel consumption rate (kg/s/eng)

δ = pressure ratio (dimensionless)

θ = temperature ratio (dimensionless)

M = Mach number (dimensionless)

f_n = fuel consumption rate (kg/s/eng)

The BFFM2 method relies on the availability of the static-condition fuel consumption rates (R_0) for different LTO modes as found in the ICAO emissions databank. The mode-specific constants represent the effect of environmental control system (ECS) usage on fuel consumption. The ICAO emissions tests are conducted without ECS in operations; the mode-specific constants account for the additional energy required to run the airplane's ECS. Nominal values for the mode-specific constants are given in [Table 2](#):

Table 2 - LTO specific modes for use with Equation 1

LTO Mode	Mode-Specific Constant
Take-off	1.010
Climb-out	1.013
Approach	1.020
Idle	1.100

The mode-specific constants are averages for a number of different airplane types. Users of this AIR are encouraged to replace the nominal values in [Table 2](#) with airplane-specific constants if those data are available.

4.3 Terminal Area Model

In the terminal area model, a terminal area thrust specific fuel consumption (TSFC) method for the operational type (i.e., departures or arrivals) is used. The terminal area model is intended to only be used for airplanes with turbofan engines in the terminal area of the airport. The terminal area model defines the fuel consumption rate for each engine. The model units of TSFC (kg/min/kN) are the same as those given in the BADA 3 model (discussed in [5.1](#)).

The airplane-specific empirical coefficients in the TSFC equations can be derived from detailed airplane or engine manufacturer's data. The data used in the derivation should represent airplane operations at a range of expected airport elevations and airplane operational states. Developers of the data should expect the data to be used up 10000 feet MSL. The methods of data development for the empirical coefficients in Equations 2 and 4 are discussed in [Appendix C](#).

The terminal area model is compatible with the EEC Aircraft Noise and Performance (ANP) database (EEC, 2021). The ANP database is based on AIR1845, with improvements documented in ICAO Doc. 9911 and ECAC Doc. 29.

4.3.1 Departure Model

For the departure model, the thrust specific fuel consumption during departures η_{dep} is calculated as:

$$\eta_{\text{dep}} = (K_1 + K_2 M + K_3 h_{\text{MSL}} + K_4 F_n / \delta) \sqrt{\theta} \quad (\text{Eq. 2})$$

where:

η_{dep} = TSFC during departure (kg/min/kN)

K_1 = airplane-specific terminal-area departure TSFC constant coefficient (kg/min/kN)

K_2 = airplane-specific terminal-area departure TSFC Mach coefficient (kg/min/kN)

K_3 = airplane-specific terminal-area departure TSFC altitude coefficient (kg/min/kN/ft)

K_4 = airplane-specific terminal-area departure TSFC thrust coefficient (kg/min/kN/lb)

h_{MSL} = airplane altitude (feet, MSL)

M = airplane Mach number (dimensionless)

θ = ratio of temperature at the airplane's altitude to sea level ISA temperature (dimensionless)

δ = ratio of pressure at the airplane's altitude to sea level ISA pressure (dimensionless)

F_n / δ = airplane corrected net thrust per engine (lbf)

The terminal area departure TSFC model contains a corrected net thrust term which uses imperial units (lbf) for the airplane thrust. The corrected net thrust parameter in the thrust term can come from data sources derived from AIR1845, which also uses imperial units (EEC, 2021).

The fuel consumption rate per engine f_{ndep} (kg/min/eng) during terminal area departure operations is:

$$f_{\text{ndep}} = \eta_{\text{dep}} F_n \quad (\text{Eq. 3})$$

where:

F_n = aircraft net thrust per engine (kN)

4.3.2 Arrival Model

For the terminal area arrival model, the TSFC during arrivals is calculated as:

$$\eta_{\text{arr}} = \left(\alpha + \beta_1 M + \beta_2 e^{-\left(\frac{\beta_3 F_n / \delta}{F_{n0}}\right)} \right) \sqrt{\theta} \quad (\text{Eq. 4})$$

where:

η_{arr} = TSFC during arrival (kg/min/kN)

α = airplane-specific terminal-area arrival TSFC constant coefficient (kg/min/kN)

β_1 = airplane-specific terminal-area arrival TSFC Mach coefficient (kg/min/kN)

β_2 = airplane-specific terminal-area arrival TSFC thrust coefficient (kg/min/kN)