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Turbofan Specific Fuel Consumption, Size and Mass from Correlated Engine Parameters

Simple but reliable engine black box models are needed in aircraft analysis and design.

The specific fuel consumption (SFC) characterizes the efficiency of an aircraft's engine. For a jet engine, the thrust specific fuel consumption is defined as the fuel mass consumed per unit thrust and per unit time (kg/N/s). SFC changes with aircraft speed (V) and altitude (h). The knowledge of SFC is fundamental for calculations in flight mechanics and aircraft design. In aircraft design also engine mass is important, because it adds to the aircraft overall mass. Engine size is important for engine integration.

PURPOSE

Simple equations and more extended models are developed to determine characteristic engine parameters: Specific fuel consumption (SFC), engine mass, and engine size characterized by engine length and diameter. SFC written with variable c is considered a linear function of speed: $c = c\_a * V + c\_b$. $c\_b = c\_0$ is the SFC at Mean Sea Level (MSL) at take-off thrust and zero speed.

METHODOLOGY

Data from 718 engines is collected from various open sources into an Excel spreadsheet. The characteristic engine parameters are plotted as function of bypass ratio (BPR), date of entry into service (EIS), take-off thrust, and typical cruise thrust. Engine mass is plotted versus take-off thrust. Engine volume, density, diameter, and length are plotted versus take-off thrust, and BPR. Linear and nonlinear regression functions are investigated. Moreover, Singular Value Decomposition (SVD) is used to establish relations between parameters. SVD is used with Excel and MATLAB. The best equations are selected.

FINDINGS

SFC should be calculated as a linear function of speed. This is especially important, when SFC is extrapolated to unconventional (low) cruise speeds for jet engines. The two parameters c_a and c_b are best estimated from a logarithmic or power function of bypass ratio (BPR) (Figure 1). SFC and c_b clearly improved over the years (Figure 3). Engine mass is proportional to take-off thrust. Diameter is a function of engine mass. Engine density and l_e / D_e are a function of BPR (Figure 2). Parameters can also be obtained from SVD with comparable accuracy. However, SVD is more complicated to set up.

Table 1: Parameters, variables and units as used.

parameter	variable	unit
thrust	T	N
SFC	C	kg/(Ns)
SFC parameter	C_a	kg/(Nm)
SFC parameter	C_b	kg/(Ns)
engine mass	m_e	kg
engine diameter	D_e	m
engine length	l_e	m
engine volume	V_e	m³
cruise speed	V	m/s
BPR	λ	-
year of EIS	n_{EIS}	-

$$C_a = 3.962 \cdot 10^{-8} \cdot C_0^{5.288 \cdot 10^{-3}}$$

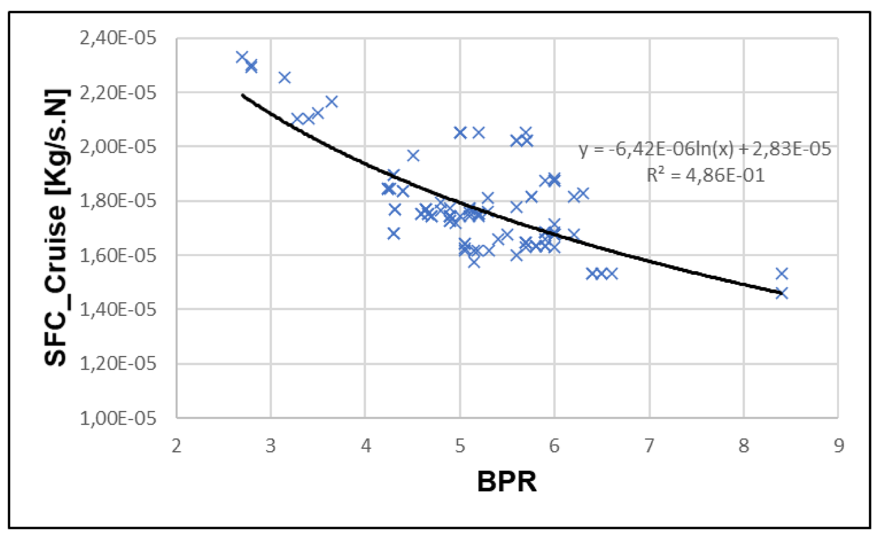
R^2	Err [%]
0,.4	8.84

$$C_b = 1.649 \cdot 10^{-5} \cdot \lambda^{-0.3940}$$

R^2	Err [%]
0.5	5.81

Figure 1: Basic equations for c_a and c_b. c_0 is the SFC at MSL with take-off thrust ($V = 0$). c_b is its estimate.

$$C = 3.738 \cdot 10^{-8} \cdot \lambda^{-2.084 \cdot 10^{-3}} \cdot V + 1.649 \cdot 10^{-5} \cdot \lambda^{-0.3940}$$



$$C = -6.42 \cdot 10^{-6} \ln(\lambda) + 2.83 \cdot 10^{-5}$$

<u>Abbreviations</u>
- BPR: Bypass Ratio
- SFC: Specific Fuel Consumption (here: with respect to thrust)
- EIS: year of Entry Into Service
- TO: Take-Off
- MSL: Mean Sea Level

Figure 1: SFC: Recommended equation (red) built from Figure 1; average error: 6.16% and R²: 0.23. Below: SFC-equation from a single dependance, here BPR.

PRACTICAL IMPLICATIONS

Engine characteristics need to be estimated based on only a few known parameters for aircraft preliminary sizing, conceptual design, and aircraft optimization as well as for practical quick calculations in flight mechanics. This thesis provides the tools.

SOCIAL IMPLICATIONS

Most engine characteristics like SFC are considered company secrets. The availability of open access engine data is the first step, but wisdom is retrieved only with careful analysis of the data as done here. Openly available aircraft engineering knowledge helps to democratize the discussion about the ecological footprint of aviation.

ORIGINALITY / VALUE

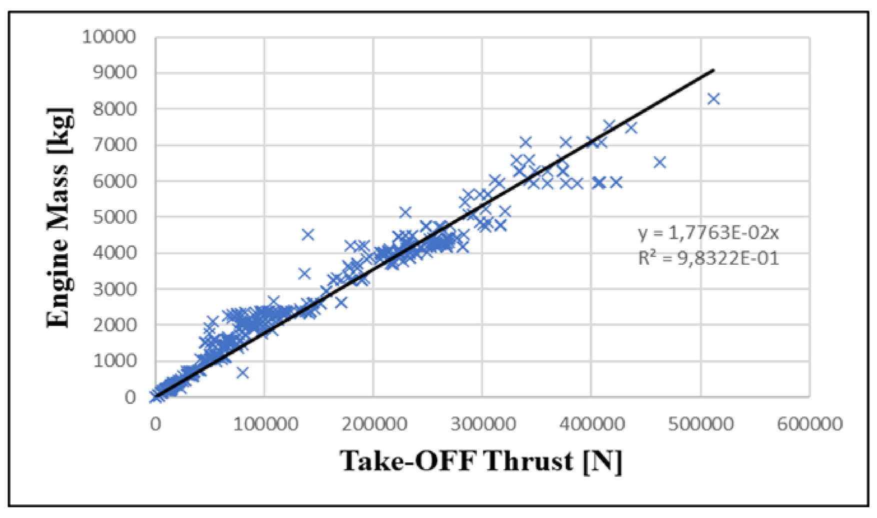
Simple equation for jet engine SFC, mass, and size deduced from a large engine database are offered. This approach delivered equations as a function of BPR with an error of only 6%, which is the same accuracy as more complex equations from literature.

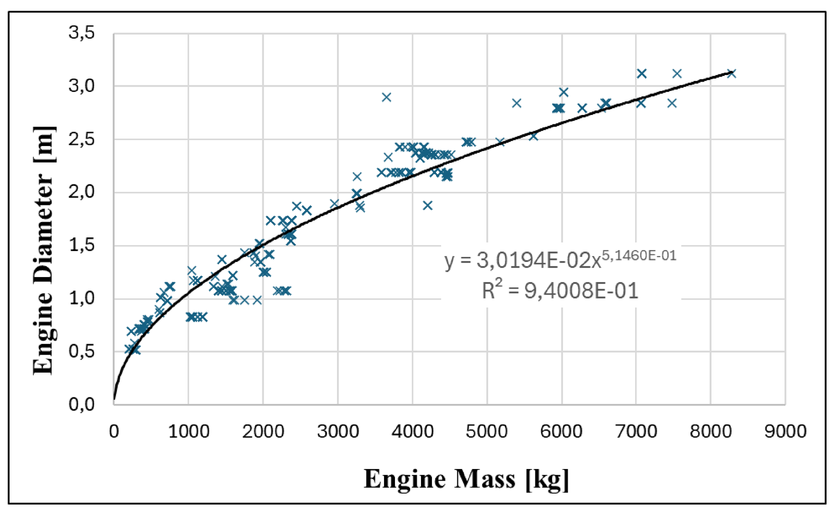
MAIN SOURCE

MEIER, Nathan, 2005. Civil Turbojet/Turbofan Specifications. Available from: https://www.jet-engine.net/civtfspec.htm.

NEW ENGINE DATABASE

https://purl.org/aero/EngineDatabase/html 30 datapoints per engine





$$m_e = 1.776 \cdot 10^{-2} \cdot T_{TO}$$

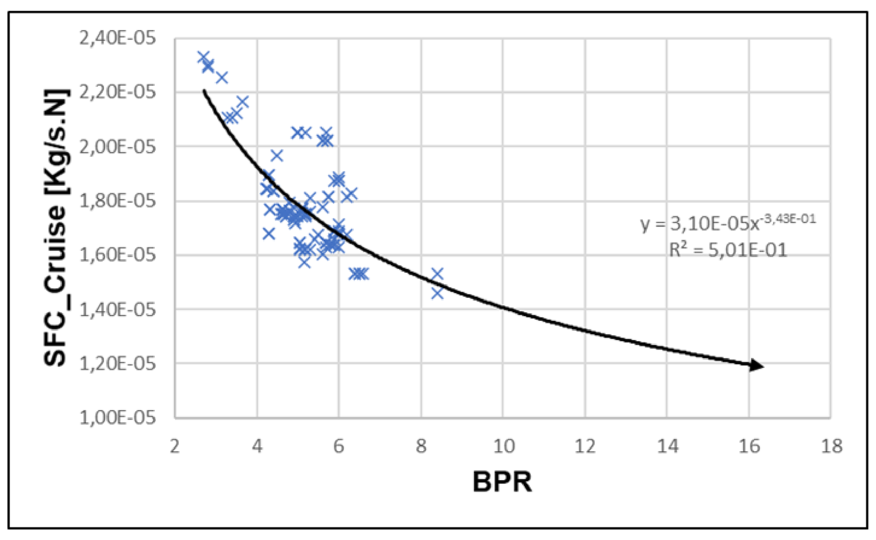
V_e and l_e from:

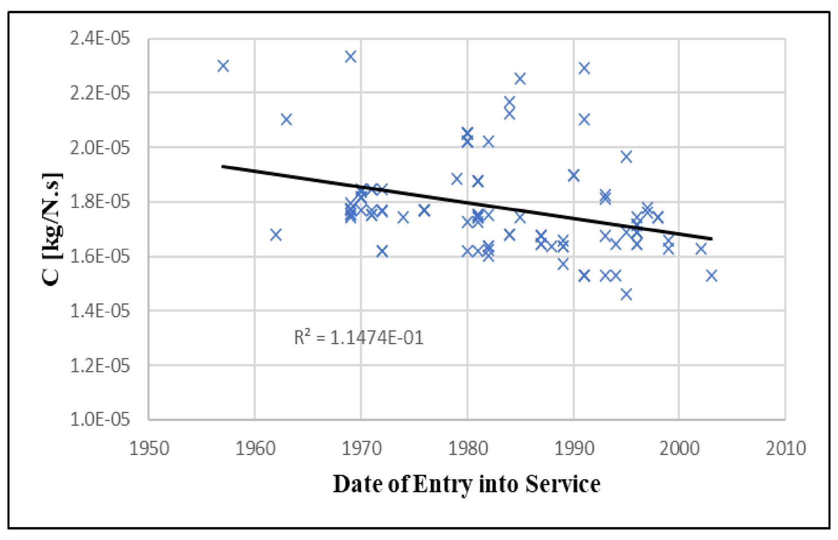
$$\rho_e = \frac{m_e}{V_e} = 478.1\ \lambda^{-0.3503} \qquad \frac{l_e}{D_e} = 2.959\ \lambda^{-0.3125}$$

$$D_e = 3.019 \cdot 10^{-2}\ m_e^{0.5146}$$

Check: $V_e = \frac{\pi}{4} \cdot D_e^2 \cdot l_e$

Figure 2: Equations for engine mass, volume, diameter and length.





$$C = 3.10 \cdot 10^{-5}\ \lambda^{-0.343}$$

$$C = -6.0 \cdot 10^{-8}(n_{EIS} - 1980) + 1.8 \cdot 10^{-5}$$

Figure 3: Future trends: SFC improvements with BPR are less pronounced with high BPR. Yes, SFC has been reduced over the decades (by 0.33% p.a.), but this trend is not that clear for all engines.

All details in the Master Thesis of Hammami (2021):
https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2021-09-15.018

Associated research data (Harvard Dataverse):
https://doi.org/10.7910/DVN/UW6FAP

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