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**Turbofan Engine Maintenance Cost Estimation
for Preliminary Aircraft Design –
Empirical Regression
with Thrust and Flight-Cycle Length**

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Technical Note

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19. Abstract An empirical preliminary-design equation is derived for planned turbofan engine maintenance reserve as a function of rated take-off thrust, T and flight-cycle length, $L = EFH/EFC$. 35 published maintenance cost observations are normalized to 2025 USD with the U.S. Consumer Price Index for All Urban Consumers (CPI-U) and fitted separately for small/medium and large engines. The recommended model is piecewise linear of the form $C = a + b \cdot T + d/L$. Power-law relations are discussed as sensitivity checks. The text documents calibration limits, source traceability, specific maintenance cost per rated thrust, C/T , and an example of a four-versus-two-engine comparison. Application to preliminary aircraft design is demonstrated by engine-number trades at constant total installed thrust, including four-versus-two-engine examples and a discussion of the limits of extending the approach towards distributed propulsion.		
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Extended Abstract

Purpose – The objective is to derive an easy-to-use empirical equation for turbofan engine maintenance cost in preliminary aircraft design, particularly for configuration studies varying engine number and thrust while retaining flight-cycle severity.

Methodology – Published maintenance-reserve data for civil turbofan engines were compiled primarily from Aircraft Commerce. Planned engine maintenance reserve is modeled as a function of rated take-off thrust, T , and flight-cycle length, $L = \text{EFH}/\text{EFC}$. Historical costs were normalized observation by observation to 2025 USD using the U.S. Consumer Price Index for All Urban Consumers (CPI-U). Separate regressions were fitted for small/medium and large engines.

Findings – The data set contains 35 observations. The recommended piecewise linear model has the form $C = a + b T + d/L$. Power-law alternatives, $C = k T^m + d/L$, provide sensitivity checks but do not improve the overall fit. Specific maintenance cost, C/T , reveals a critical flight-cycle length L_{crit} , at which the effect of thrust on C/T changes sign.

Research Limitations – The data are published maintenance-budget estimates rather than standardized airline cost accounts. The sample is limited, contains an observation gap between 41.7 and 53.5 klbf, and covers only $1.2 \leq L \leq 3.0$ for small/medium engines. Extrapolation therefore requires caution.

Practical Implications – The equations connect two basic aircraft-design quantities – engine thrust and flight-cycle length – to recurring engine-maintenance cost. At fixed total installed thrust, they can be reformulated in terms of engine number. Four-versus-two-engine examples demonstrate both the usefulness and limitations of such trades and lead to a discussion of distributed propulsion.

Social Implications – Transparent equations based on traceable public data make engine-maintenance economics accessible beyond industry specialists and can broaden the factual basis for public and academic discussion of aircraft design and propulsion.

Originality – Maintenance-cost models using thrust and operational severity exist. The distinctive contribution here is their reduction to a transparent piecewise preliminary-design relation, combined with analytical treatment of C/T , its critical flight-cycle length, and engine-number trades at fixed total thrust.

Table of Contents

List of Figures	6
List of Tables.....	6
List of Symbols	7
List of Abbreviations.....	8
List of Definitions	9
1 Introduction	17
1.1 Motivation	17
1.2 Objective and Scope	17
1.3 Structure	18
2 Data Basis and Cost Definition.....	19
2.1 Maintenance-Cost Quantity.....	19
2.2 How Engine Maintenance Costs Arise.....	19
2.3 Flight-Cycle Length	21
2.4 Sources and Observations	21
3 Method.....	23
3.1 Inflation Normalization	23
3.2 Regression Form.....	23
3.3 Piecewise Classification	24
3.4 Statistical Measures	24
4 Piecewise Maintenance-Cost Model.....	25
4.1 Recommended Linear Equations.....	25
4.2 Graphical Representation of the Linear Equation	25
4.3 Alternative Power-Law Equations	26
4.4 Graphical Comparison of the Linear and the Power-Law Equation	27
4.5 Graphical Representation of the Power-Law Equation	28
5 Specific Engine Maintenance Cost, C/T	30
5.1 Motivation	30
5.2 Specific-Cost Equations	30
5.3 Graphical Interpretation	30
5.4 Interpretation for Aircraft Design.....	31

6	Discussion	32
6.1	Plausibility of the Flight-Cycle Term.....	32
6.2	Applicability, Extrapolation and Sample Size	32
6.3	Inflation and Cost Escalation	32
6.4	Current Engine-MRO Environment and Cost Escalation	33
6.5	Application to Engine-Number Trades	34
7	Application	34
7.1	Engine-Number Trade in Preliminary Aircraft Design.....	34
7.2	Example 1: Aircraft of the Size of an Airbus A340	35
7.3	Specific Cost and the Apparent Contradiction in Example 1.....	36
7.4	Example 2: Aircraft of the Size of an Airbus A380	37
7.5	From Few Engines to Distributed Propulsion	38
8	Summary	41
9	Conclusions and Recommendations	42
	List of References	43
	Appendix A – Regression Data	46
	Appendix B – Repeated-L Plausibility Checks.....	49

List of Figures

Figure 4.1	Engine Maintenance Cost Versus Rated Take-Off Thrust for the Recommended Linear Regression	26
Figure 4.2	Small/Medium Engines: Linear Versus Power-Law Regression	27
Figure 4.3	Large Engines: Linear Versus Power-Law Regression.....	28
Figure 4.4	Engine Maintenance Cost Versus Thrust Using the Piecewise Power-Law Model.....	29
Figure 5.1	Specific Engine Maintenance Cost C/T from the Recommended Linear Equations	31

List of Tables

Table A.1	Observation-Level Regression Data and 2025-Dollar Normalization	46
Table A.2	Values of the Consumer Price Index (CPI) from BLS 2008, BLS 2009, and BLS 2026	48

List of Symbols

Symbol	Meaning	Unit
a	constant / regression coefficient	USD/EFH
A_{disc}	propeller or fan disc area	m ²
b	thrust regression coefficient	USD/(EFH·klbf)
b_w	wing span	m
C	engine maintenance cost	USD/EFH
C_{LLP}	life-limited-part maintenance reserve	USD/EFH
C_{shop}	planned engine shop-visit reserve	USD/EFH
C_y	engine maintenance cost in source year y	USD/EFH
C_{2025}	engine maintenance cost normalized to 2025 USD	USD/EFH
d	cycle-related regression coefficient	USD/EFC
D	propeller or fan diameter	m
EFC	engine flight cycles	—
EFH	engine flight hours	h
F_y	inflation factor from source year y to 2025	—
g	minimum clearance between propellers; short: gap	m
I_y	CPI-U annual-average index in source year y	—
L	flight-cycle length (i.e. time), EFH/EFC	h/cycle
L_{crit}	critical flight-cycle length at which the effect of thrust on C/T changes sign	h/cycle
n	number of observations	—
n	number of engines	—
R^2	coefficient of determination	—
T	rated take-off thrust of one engine	klbf
T_Σ	rated take-off thrust of all engines of an aircraft	klbf
y	source year	—

List of Abbreviations

AC	Aircraft Commerce (Trade Journal)
AOG	Aircraft On Ground
BLS	Bureau of Labor Statistics
CPI	Consumer Price Index
CPI-U	Consumer Price Index for All Urban Consumers
EFC	Engine Flight Cycle
EFH	Engine Flight Hour
FAA	Federal Aviation Administration
IATA	International Air Transport Association
LLP	Life-Limited Part
MMH	Maintenance Man-Hour
MRO	Maintenance, Repair and Overhaul
OEM	Original Equipment Manufacturer
RMSE	Root-Mean-Square Error
RTC	Reduced-Thrust Climb
USD	United States Dollar

List of Definitions

aircraft-on-ground (AOG)

A condition in which an aircraft cannot continue in service because remedial technical or maintenance action is required. *AOG* is also used operationally to indicate the high priority of parts or services required to return such an aircraft to service.

<https://www2.anac.gov.br/anacpedia/sig/tr2357.htm>

burden

Something that imposes a load, responsibility, difficulty, or cost. In this Technical Note, *burden* is used in the economic rather than physical sense: the amount of maintenance expenditure associated with operating an engine. Because the word is less precise than *cost*, it should preferably be qualified, e.g. *maintenance burden*.

<https://dictionary.cambridge.org/dictionary/english/burden>

coefficient of determination, R^2

A dimensionless statistical measure describing how much of the observed variation of the dependent variable is accounted for by a regression model. $R^2 = 1$ corresponds to a perfect fit to the observations; a high R^2 does not by itself establish causality or predictive validity outside the calibration data.

https://scikit-learn.org/stable/modules/model_evaluation.html, archived at:
<https://perma.cc/7Y4W-W84U>

Consumer Price Index (CPI)

An index measuring the average change over time in prices paid by consumers for a representative basket of goods and services.

<https://www.bls.gov/bls/faqs.htm>

Consumer Price Index for All Urban Consumers (CPI-U)

The CPI covering the U.S. population represented by all urban consumers. The broad U.S. CPI-U for the U.S. city average and all items is the index used in this Technical Note to convert historical maintenance-cost observations to a common dollar year.

<https://www.bls.gov/bls/faqs.htm>

cost

The amount of money required to buy, perform, produce, or otherwise obtain something. In this Technical Note, cost refers to monetary expenditure or to an economically equivalent maintenance reserve.

cost escalation

An increase in the monetary cost of a particular good, service, or activity over time. It can differ from general inflation because the prices of the particular labor, material, capacity, or services

involved may change faster or slower than the general price level. In this Technical Note, *MRO cost escalation* therefore denotes maintenance-specific price development beyond, or different from, general CPI inflation.

cycle

A recurring sequence of operation. In this Technical Note, unless stated otherwise, a cycle refers to an aircraft/engine operating cycle associated with one flight rather than, for example, a thermodynamic engine cycle.

cycle count

The accumulated number of operating or flight cycles experienced by an aircraft, engine, or component. For life-limited engine parts, cycle count is an important measure of accumulated life usage. FAA rules require maximum allowable flight-cycle limits for engine life-limited parts.

<https://www.faraim.org/faa/far/cfr/title-14/part-33/section-33.70.html>

engine flight cycle (EFC)

One unit of accumulated engine cyclic operation. For the present cost model it is taken as the engine cycle associated with one aircraft flight. More formally, EASA defines an *Engine Flight Cycle* as the flight profile, or combination of profiles, on which the approved life of an engine critical part is based.

<https://bit.ly/4hMPkmk>, archived at: <https://perma.cc/M9MZ-GWBR>

engine flight-cycle length, $L = \text{EFH}/\text{EFC}$

The average number of engine flight hours accumulated per engine flight cycle. It is therefore approximately the average flight time per flight cycle. A larger L represents longer average flight time and fewer cycles per flight hour.

Definition specific to this Technical Note.

engine flight hours (EFH)

Accumulated engine operating time expressed in flight hours. In engine service agreements, EFH is commonly measured from aircraft wheels-up to wheels-down.

<https://bit.ly/4hdIzdl>

engine maintenance cost

Monetary expenditure is attributable to maintaining an engine and its associated components. Depending on the accounting boundary, it may include line maintenance, engine removals, shop visits, repair and replacement material, labor, life-limited parts, and unscheduled maintenance. *In this Technical Note the modeled quantity is deliberately narrower and is represented only by planned shop-visit and LLP reserves.*

engine maintenance reserve

A provision accumulated in relation to engine utilization to fund future major engine maintenance. Maintenance reserves are commonly collected against engine performance restoration on a flight-hour basis and engine LLP replacement on a flight-cycle basis.

<https://bit.ly/4d76rwJ>

engine maintenance reserve per engine flight hour

Engine maintenance reserve divided by accumulated engine flight hours, expressed here in USD/EFH. It converts expected future maintenance expenditure into a utilization-related hourly amount.

Definition specific to this Technical Note.

flight cycle

One complete aircraft operating cycle associated with a flight, normally including take-off and landing. For engine-life purposes, the precise cycle or mission profile may be defined by the engine manufacturer and certification basis; see *engine flight cycle*.

flight-cycle length

The average flight time associated with one flight cycle. In this Technical Note it is quantified by $L = \text{EFH}/\text{EFC}$.

inflation

The general upward movement of prices of goods and services in an economy.

<https://www.bls.gov/bls/inflation.htm>

klbf

One thousand pounds-force: $1 \text{ klbf} = 1000 \text{ lbf} \approx 4.44822 \text{ kN}$. The unit is used here for rated engine thrust.

lbf

Pound-force, a non-SI unit of force. One pound-force is the force corresponding to one avoirdupois pound mass under standard gravity; $1 \text{ lbf} = 4.44822 \text{ N}$.

<https://www.nist.gov/glossary-term/29611>

life-limited part (LLP)

A part for which a mandatory replacement limit is specified. For turbine engines, FAA requirements establish approved lives for engine life-limited structural parts whose primary failure could result in a hazardous engine effect.

<https://www.ecfr.gov/current/title-14/section-43.10>

<https://www.ecfr.gov/current/title-14/section-33.70>

life-limited-part maintenance reserve

A utilization-related monetary provision for the future replacement of engine LLPs when their approved lives are consumed. Because engine LLP lives are predominantly cycle-controlled, this reserve is normally related to accumulated flight cycles.

Definition as used in this Technical Note, consistent with common maintenance-reserve practice. <https://bit.ly/4d76rwJ>

life-limited-part reserve (LLP reserve)

See *life-limited-part maintenance reserve*.

LLP consumption

The portion of the approved life of an LLP used during operation. For a cycle-limited part, one additional applicable flight cycle consumes one cycle of its remaining approved cyclic life. The corresponding economic consumption is the fraction of eventual replacement cost attributable to that utilization.

maintenance

The performance of tasks required to ensure the continuing airworthiness of an aircraft, engine, propeller, or associated part. Such tasks may include overhaul, inspection, replacement, defect rectification, modification, and repair. This usage follows the established ICAO aviation definition.

<https://bit.ly/4z34ZE9>

maintenance burden

The economic load imposed by maintenance on an operator. In this Technical Note it denotes maintenance expenditure or an equivalent maintenance reserve associated with engine operation. It is a descriptive engineering-economic term rather than a formally standardized aviation accounting quantity.

maintenance cost

Monetary expenditure attributable to performing maintenance, including applicable labor, material, repair, replacement, and external maintenance services according to the cost boundary selected for the analysis.

maintenance man-hour (MMH)

One hour of maintenance labor performed by one maintenance person. MMH is a measure of maintenance labor input; multiplication by an applicable labor rate gives the corresponding direct labor cost.

maintenance, repair and overhaul (MRO)

A collective term for the activities and industry concerned with maintaining, repairing, and overhauling aircraft, engines, and components so that they remain or are returned to an airworthy condition.

mission

The operational task or flight that an aircraft is intended to perform. In the present analysis, a mission is characterized particularly by its flight duration and hence by its contribution to EFH and EFC. Thus, for repeated similar missions, mission duration strongly influences $L = \text{EFH}/\text{EFC}$.

number of observations, n

The number of individual data points used in a statistical analysis or regression. In this Technical Note, repeated observations for the same engine family at different L are separate observations, although they are not necessarily statistically independent observations of different engine designs.

original equipment manufacturer (OEM)

The manufacturer of the original equipment or system. In this Technical Note, *engine OEM* denotes the manufacturer responsible for the engine design and associated manufacturer documentation; examples include engine manufacturers rather than airlines or independent MRO providers.

planned engine maintenance reserve per engine flight hour

The estimated planned engine-maintenance expenditure allocated to one engine flight hour. In this Technical Note it is the principal dependent variable and consists essentially of the *planned shop-visit reserve plus the LLP reserve*, excluding identifiable unscheduled-maintenance cost. It is expressed in USD/EFH.

Definition specific to this Technical Note.

planned maintenance burden

The portion of the maintenance burden associated with maintenance that can be anticipated and budgeted as part of the normal maintenance process, rather than maintenance arising from unforeseen events.

Definition specific to this Technical Note.

positive-valued relation

A mathematical relation whose calculated dependent variable remains greater than zero over the stated domain. In this Technical Note, the term describes the advantage of the power-law cost equation in yielding positive maintenance cost for positive T and L .

power-law equation

An equation in which one quantity varies as a constant multiplied by another quantity raised to a power, conventionally $y = ax^b$. The alternative maintenance-cost model in this Technical Note combines such a thrust term with the cycle-related term d/L : $C = aT^b + d/L$.

proxy

A measurable variable used in place of another quantity that is unavailable, difficult to measure, or too complex to represent directly. In this Technical Note, rated thrust is used as a proxy for engine size and associated material/maintenance exposure, while $1/L$ is a proxy for cycle intensity per flight hour.

<https://bit.ly/4xOPvCG>

rated thrust

A formally specified thrust rating of an engine under defined operating and environmental conditions. Because one engine model may have several ratings, *rated thrust* must be associated with the applicable engine variant and rating condition.

rated take-off thrust, T

The engine thrust rating applicable to take-off under the rating conditions specified for the engine. It is the thrust quantity used as the independent size variable T in this Technical Note and is expressed in klbf.

recurring maintenance burden

Maintenance expenditure that arises repeatedly as the aircraft or engine is operated, in contrast to a one-time development, acquisition, or modification expenditure.

Definition specific to this Technical Note.

recurring planned maintenance burden

The repeatedly incurred, foreseeable portion of maintenance expenditure associated with normal utilization. In this Technical Note it is the conceptual cost quantity that the planned shop-visit and LLP reserves are intended to represent.

Definition specific to this Technical Note.

repeated- L check

A check of the assumed dependence on flight-cycle length using several cost observations for the *same engine or engine group at different values of L* . It reduces the confounding effect of engine size and technology when testing the proposed $1/L$ dependence.

Term introduced for the analysis in this Technical Note; not a standardized maintenance term.

reserve

Money or an accounting provision accumulated or allocated for an expected future expenditure. In aircraft leasing, maintenance reserves are typically utilization-related payments intended to provide funds toward future major maintenance events.

<https://bit.ly/4d76rwJ>

reserve rate

The amount of maintenance reserve accrued per unit of utilization, for example USD per flight hour or USD per flight cycle. A maintenance reserve rate can be estimated from the expected cost of a maintenance event divided by the expected utilization interval between such events.

<https://www.jdsupra.com/legalnews/maximizing-returns-through-effective-31149>

root-mean-square error (RMSE)

A measure of the typical magnitude of model residuals, calculated as the square root of the mean of the squared errors. It has the same unit as the modeled quantity. Thus, an RMSE of 40 USD/EFH indicates a regression-error magnitude on the order of tens of USD/EFH; it does *not* mean that every prediction is within 40 USD/EFH.

https://scikit-learn.org/stable/modules/model_evaluation.html

archived at: <https://perma.cc/7Y4W-W84U>

scheduled maintenance

Maintenance consisting of individual maintenance tasks performed according to specified maintenance time limitations or a maintenance schedule.

https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC120-16D.pdf

shop visit

Removal/induction of an engine into an engine maintenance shop for maintenance requiring substantial off-wing work. The exact contractual or OEM definition varies. For example, CFM defines a shop visit through specified major engine disassembly or LLP-removal criteria. In this Technical Note, *shop visit* refers generally to an off-wing engine maintenance event of the type generating the shop-maintenance costs represented by the source data.

<https://pdfcoffee.com/cfm56-5b-sb-rev-72-0912-tsn02-r-20210414-pdf-free.html>

shop-visit reserve

A utilization-related monetary provision for an expected future engine shop visit. In this Technical Note it represents the planned shop-maintenance portion of the engine maintenance reserve, excluding the separately identified LLP reserve where the source data permit this separation.

specific maintenance cost, C/T

Engine maintenance cost, C divided by rated take-off thrust T , expressed in this Technical Note in USD/(EFH·klbf).

It is an aircraft design diagnostic introduced in this Technical Note, not a standard MRO accounting metric. It permits comparison of maintenance cost relative to engine thrust or approximate engine size.

thrust, T

The propulsive force produced by an engine. For an aircraft, thrust acts to propel the aircraft and overcome aerodynamic drag. In this Technical Note T specifically denotes rated take-off thrust.

<https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/what-is-thrust>

unscheduled maintenance

Maintenance occurring on an unscheduled or unforeseen basis. It may result from defects discovered during scheduled maintenance, pilot reports, malfunctions, or events such as hard landings, lightning strikes, or engine overtemperature.

https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC120-16D.pdf

unscheduled removal

Removal of an engine or component from service because of an unplanned technical condition, fault, deterioration, damage, or other event, rather than at a predetermined planned removal point. An unscheduled engine removal does not necessarily imply that the subsequent maintenance qualifies as a major shop visit.

U.S. CPI-U

The U.S. Consumer Price Index for All Urban Consumers. In this Technical Note the intended series is *U.S. city average, all items*, used to normalize historical U.S.-dollar maintenance costs to a common price year.

<https://www.bls.gov/bls/faqs.htm>

1 Introduction

1.1 Motivation

Engine maintenance cost is an important direct operating cost and can influence aircraft configuration. A particularly instructive preliminary-design question is whether a long-range aircraft should use four smaller turbofan engines or two larger engines providing approximately the same total installed thrust. A simple cost model should therefore capture both the effect of rated thrust and the effect of flight-cycle length without requiring engine-specific maintenance-program detail.

Published engine-maintenance analyses show that reserve rates depend strongly on flight hours per engine flight cycle. Short cycles increase the cost per flight hour because cycle-driven deterioration, removals and life-limited-part consumption are spread over fewer flight hours. A thrust-only correlation consequently mixes engine size with mission severity and is unsuitable as a general preliminary-design relation.

1.2 Objective and Scope

The objective of this Technical Note is to document an empirical maintenance-cost estimating relationship for civil turbofan engines. The preferred model shall be transparent, use variables available during preliminary aircraft design, and retain enough statistical quality to support configuration comparisons. The principal independent variables are rated take-off thrust, T and flight-cycle length, $L = \text{EFH}/\text{EFC}$. The dependent variable is a planned maintenance reserve consisting of planned shop-visit reserve and life-limited-part reserve.

The work focuses on the final estimating relations and their scientific basis. Exploratory model forms that did not lead to a convincing description of engine maintenance costs are not reproduced here in detail. Only a large-engine power-law alternative is retained because it avoids a negative intercept and provides a useful sensitivity check.

1.3 Structure

Chapter 2	defines the maintenance-cost quantity and provides the engineering maintenance context.
Chapter 3	describes inflation normalization and regression methodology.
Chapter 4	presents the recommended piecewise linear equations, the alternative power-law equations, and graphical comparisons of both forms.
Chapter 5	examines the specific maintenance cost C/T derived from the recommended linear model and discusses its dependence on thrust and flight-cycle length.
Chapter 6	discusses plausibility and applicability.
Chapter 7	applies the results to aircraft designs with different numbers of engines.
Chapters 8 and 9	provide a summary, conclusions, and recommendations.
Appendix A	lists the observation-level data.
Appendix B	checks given data for plausibility, where data is given for the same engine with different values of engine flight-cycle length (i.e. time), L .

2 Data Basis and Cost Definition

2.1 Maintenance-Cost Quantity

The cost quantity used for regression is the planned engine maintenance reserve per engine flight hour. Where the source separates the elements, it is defined as

$$C = C_{shop} + C_{LLP} \quad (1)$$

Unscheduled-event allowances are excluded where the source allows a consistent separation. This choice reduces the influence of exceptional events and keeps the model directed toward the recurring maintenance burden required for preliminary design.

2.2 How Engine Maintenance Costs Arise

For aircraft design engineers, it is useful to distinguish the accounting categories of engine maintenance from the physical deterioration mechanisms. At airline level, engine-related maintenance expenditure can include on-wing line maintenance, scheduled and unscheduled troubleshooting, borescope inspections, servicing and minor component replacement, removal and installation labor, off-wing shop visits, repair or replacement of modules and piece parts, life-limited-part replacement, spare-engine support, and – in some accounting systems – contract or lease charges. Different published sources include different subsets of these items; this is one reason why apparently similar “engine maintenance cost” figures are not always directly comparable.

Line maintenance is performed with the engine installed on the aircraft and usually involves inspection, servicing, fault isolation and comparatively minor corrective work. Shop maintenance is performed after engine removal and can require engine disassembly, module refurbishment, part repair or replacement, reassembly and test. Shop visits dominate the large, episodic expenditures that maintenance-reserve models seek to smooth into a cost per engine flight hour.

A planned engine shop-visit reserve is therefore a budgeted amount accumulated per engine flight hour to pay for expected future shop visits. It is not a labor-only quantity. A shop-visit invoice contains maintenance man-hours (MMH) multiplied by labor rates, but the material content – new parts, repaired parts and exchanged modules – can be equally or more important. Workslope escalation caused by additional findings during disassembly can increase the invoice substantially.

A life-limited part (LLP) is a rotating or other critical engine part for which an approved life limit is specified, normally in form of flight cycles. The part must be removed from service before that life is exhausted regardless of its apparent condition. An LLP maintenance reserve converts the expected future cost of these mandatory replacements into a cost per engine flight hour. Because LLP consumption is fundamentally cycle driven, its contribution naturally increases with $EFC/EFH = 1/L$.

Scheduled and unscheduled maintenance should also be separated conceptually. Scheduled work follows a planned inspection, removal or life-consumption logic; unscheduled work follows faults, damage, premature deterioration or other unexpected findings. The present regression uses planned shop-visit and LLP reserves where the source permits that separation. It therefore estimates the recurring planned maintenance burden, not the full financial consequence of every engine-related disruption. Unscheduled removals, aircraft-on-ground effects, spare-engine leasing and revenue loss can be important in airline operation but are intentionally outside the central regression.

The hot section – principally combustor and turbine hardware – is a major driver of shop-maintenance expenditure because it operates at high temperature and stress and contains expensive high-technology parts. Deterioration depends on thermal exposure, thrust setting, environment and cycle count. Higher rated thrust generally accompanies a larger engine and more expensive hardware, which gives a physical basis for a thrust-related cost term. Flight cycles add low-cycle fatigue, thermal cycling and LLP consumption, which gives a physical basis for the $1/L$ term. Thus, the regression variables T and L are not arbitrary statistical predictors: they are compact proxies for two major families of maintenance-cost drivers.

Aircraft and engine generation also matter. A newer design may offer better materials, diagnostics and on-wing performance, but new technology can initially suffer durability problems, immature repair schemes or constrained spare-parts supply. An older design may be technically mature with broad repair experience and used-serviceable-material availability, but aging fleets can require more frequent maintenance. These effects are not represented explicitly by a “technology year” variable because the available public data are too sparse and heterogeneous to identify such a coefficient robustly. Their influence appears instead as scatter around the fitted equations.

For more information on aircraft engine maintenance with an economic focus, please see Ackert (2011) and Seemann (2011).

2.3 Flight-Cycle Length

The flight-cycle parameter is

$$L = \frac{EFH}{EFC} \quad (2)$$

Because $L = EFH/EFC$, its reciprocal is EFC/EFH . A cycle-related reserve expressed in USD/EFC therefore becomes proportional to $1/L$ when converted to USD/EFH. This is the engineering reason for the term d/L . Same-engine observations at several flight-cycle lengths provide unusually strong evidence for this form because thrust and engine technology remain fixed while only mission severity changes; Appendix B gives the repeated- L checks.

2.4 Sources and Observations

The maintenance-reserve observations were assembled from Aircraft Commerce owner/operator guides and maintenance analyses for the CFM56-5A/-5B, V2500, RB211-535/PW2000, PW4000-94, CF6-80C2, CF6-80E1, PW4168, Trent 772 and GE90 families. Aircraft Commerce identifies the corresponding maintenance analyses by issue and date, including CFM56-5A/-5B Issue 50 (2007), CF6-80C2 Issue 48 (2006), PW4000-94 Issue 54 (2007), V2500 Issue 56 (2008), and RB211-535/PW2000 and big-twin engine analyses in Issue 59 (2008) (Aircraft Commerce 2006; 2007a; 2007b; 2008a; 2008b; 2008c).

The final regression data set contains $n = 35$ observations. Ten observations cover small/medium engines from approximately 23 klbf to 41.7 klbf; twenty-five observations cover larger engines from approximately 53.5 klbf to 112.7 klbf. The interval between the groups contains no calibration observations. Several engine families contribute repeated observations at different L . This is valuable for identifying the cycle effect, but such observations are correlated by common engine design and should not be treated as 35 fully independent draws from a population of turbofans.

Publicly accessible, consistently defined engine-maintenance cost data are uncommon. Airlines, engine original equipment manufacturers (OEMs), lessors and maintenance, repair and overhaul (MRO) providers usually treat detailed shop-visit costs, workscope and power-by-the-hour contract rates as commercially sensitive. Public sources often quote only broad market averages, combine scheduled and unscheduled cost, use different dollar years, or omit the associated EFH/EFC. For this work, observations were included only when a defensible thrust, flight-cycle length and maintenance-reserve definition could be reconstructed. More numbers could probably be found on the Internet, but simply increasing n with incomparable

observations would create an illusion of statistical strength rather than improve the estimating equation.

Accordingly, $n = 35$ should be regarded as adequate for fitting and checking a deliberately low-order preliminary-design correlation, but not as a large-sample validation. The large-engine branch has 25 observations for three fitted coefficients and is materially better supported than the small/medium branch, which has only 10 observations and a much narrower L range. Independent modern airline or OEM data would therefore be especially valuable for external validation.

3 Method

3.1 Inflation Normalization

All historical cost observations are converted directly to 2025 USD before regression. The U.S. Consumer Price Index for All Urban Consumers (CPI-U), U.S. city average, All items, annual average, not seasonally adjusted, is used as a transparent official dollar-year normalization. The CPI-U reference base is 1982 to 1984 = 100 (BLS 2008; BLS 2009; BLS 2026). For an observation reported in year y ,

$$C_{2025} = C_y \cdot \frac{CPI_{2025}}{CPI_y} \quad (3)$$

The annual-average CPI-U values used are 201.600 for 2006, 207.342 for 2007, 215.303 for 2008, and 321.943 for 2025 (BLS 2008; BLS 2009; BLS 2026). The resulting factors are 1.59694, 1.55271 and 1.49530 for observations from 2006, 2007 and 2008 respectively. Inflation is applied to each observation before regression; no single post-hoc factor is applied to fitted coefficients. The absolute CPI reference base does not affect the conversion because only the ratio of index values is used.

3.2 Regression Form

The physically motivated simple regression form is

$$C = a + bT + \frac{d}{L} \quad (4)$$

The term bT represents the thrust-related contribution and d/L represents the cycle-related contribution. The constant a is an empirical regression parameter. It is not interpreted as the maintenance cost of a zero-thrust engine. Regression calculations use the unrounded CPI-normalized observation values. Values shown in Appendix A are rounded for presentation only.

3.3 Piecewise Classification

A single relation does not describe the full thrust range satisfactorily. Separate regressions are therefore used for small/medium and large engines. A nominal division at 45 klbf is selected within the observation gap between approximately 41.7 klbf and 53.5 klbf. The division is a practical classification boundary rather than evidence for a physical discontinuity at exactly 45 klbf.

3.4 Statistical Measures

Model quality is reported with the coefficient of determination R^2 and the root-mean-square error (RMSE). R^2 indicates the fraction of variance in the observed maintenance-cost values explained by the regression within the fitted sample; values closer to one indicate a closer fit. RMSE is the square root of the mean squared prediction residual and is expressed here in 2025 USD/EFH. It gives a more directly interpretable indication of the typical size of regression error. Neither statistic proves physical causality or guarantees prediction quality outside the calibration domain. The equations are intended as preliminary-design estimating relationships rather than deterministic maintenance-program calculations.

4 Piecewise Maintenance-Cost Model

4.1 Recommended Linear Equations

The recommended estimating relationship remains the piecewise linear model. It is the simplest compact model tested and gives the best overall predictive performance. It separates a thrust-related contribution from a cycle-related contribution. In 2025 USD per engine flight hour:

$$C = -173.940 + 11.241 T + \frac{246.481}{L} \quad (5a)$$

for small/medium engines, nominally $T \leq 45$ klbf, and

$$C = -245.307 + 6.498 T + \frac{948.877}{L} \quad (5b)$$

for large engines, nominally $T > 45$ klbf.

Here T is rated take-off thrust in klbf, $L = \text{EFH}/\text{EFC}$ is flight-cycle length in hours per cycle, and C is planned engine maintenance reserve in 2025 USD/EFH. The 45-klbf division lies inside the observation gap from about 41.7 to 53.5 klbf and is a practical classification boundary, not a physical discontinuity.

The small/medium branch ($n = 10$) gives $R^2 = 0.581$ and $\text{RMSE} = 44.98$ USD/EFH; the large branch ($n = 25$) gives $R^2 = 0.858$ and $\text{RMSE} = 74.30$ USD/EFH. The combined RMSE is 67.24 USD/EFH. Calibration covers $T = 23.76$ to 41.7 klbf and $L = 1.2$ to 3.0 for the small/medium branch, and $T = 53.5$ to 112.65 klbf and $L = 1$ to 10 for the large branch.

4.2 Graphical Representation of the Linear Equation

Figure 4.1 shows the recommended linear equations. The small/medium branch is shown with dashed lines for $L = 2$ and 3, which lie within its observed range $1.2 \leq L \leq 3.0$. The large-engine branch is shown with solid lines for $L = 1$ to 10. The same color represents the same L where both branches are shown. The 42 to 53.5 klbf observation gap is shaded. Cost rises with thrust and falls as L increases because cycle-driven maintenance is distributed over more flight hours.

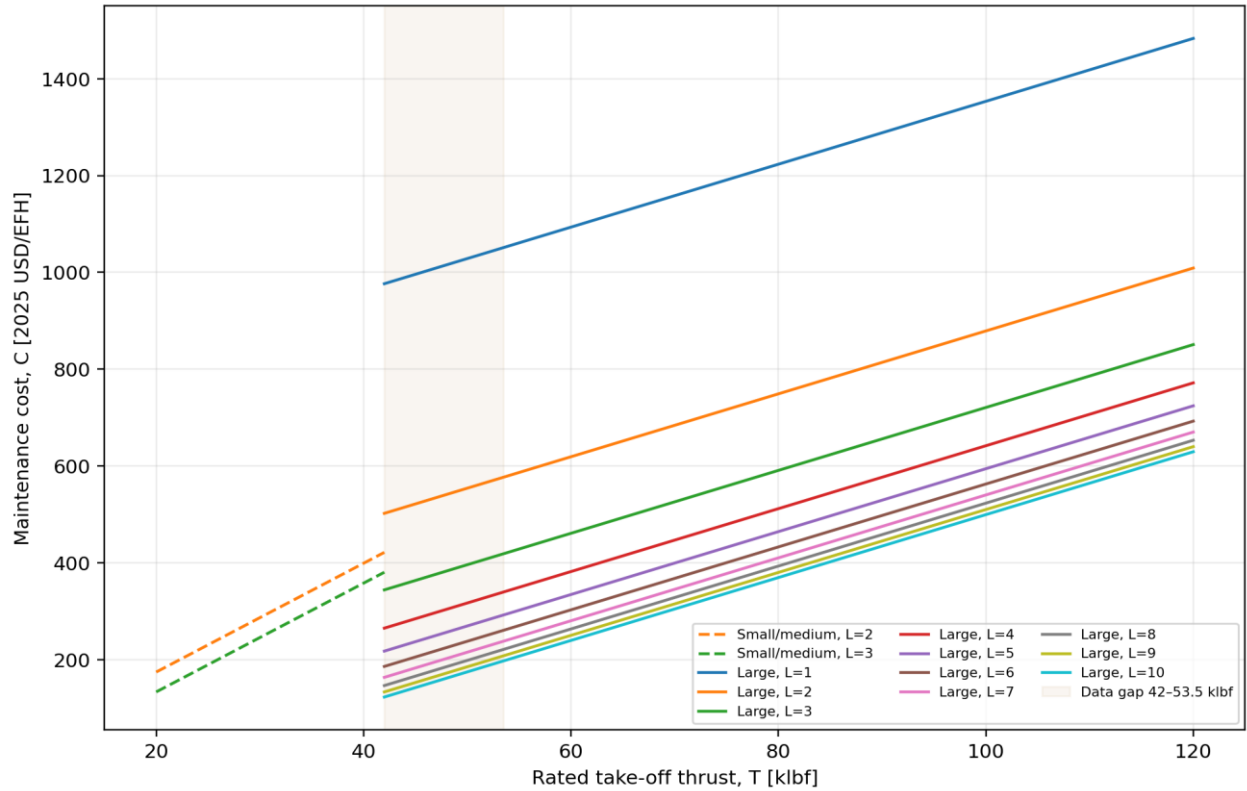


Figure 4.1 Engine maintenance cost versus rated take-off thrust for the recommended linear regression. Small/medium engines are shown for $L = 2$ and 3 only; large engines are shown for $L = 1$ to 10 . The shaded band marks the 42 to 53.5 klbf observation gap

4.3 Alternative Power-Law Equations

Power-law alternatives were fitted separately to both engine-size groups. They are useful sensitivity checks because they avoid the negative intercepts of the linear equations. “Inherently positive” here means that the functional form does not imply a negative maintenance cost when extrapolated toward low thrust; it does not imply that the power law is necessarily more physically correct.

$$C = 0.0007780 T^{3.43451} + \frac{342.061}{L} \quad (6a)$$

for small/medium engines, and

$$C = 0.256321 T^{1.58921} + \frac{899.576}{L} \quad (6b)$$

for large engines.

For small/medium engines the power law gives $R^2 = 0.634$ and $RMSE = 42.06$ USD/EFH, modestly better than the corresponding linear branch. Its fitted thrust exponent of 3.435 is difficult to interpret physically and produces increasingly rapid growth when extrapolated. For large engines the power law gives $R^2 = 0.837$ and $RMSE = 79.55$ USD/EFH, worse than the linear model. The piecewise linear model is therefore retained as the recommended preliminary-design relation.

4.4 Graphical Comparison of the Linear and the Power-Law Equation

Figures 4.2 and 4.3 compare the linear and power-law forms within the L -ranges supported by the respective datasets. Figure 4.2 therefore shows the small/medium-engine models for $L = 2$ and 3 only. Figure 4.3 shows representative large-engine cases within $1 \leq L \leq 10$. This presentation deliberately avoids using unsupported values of L merely to emphasize mathematical differences between the model forms.

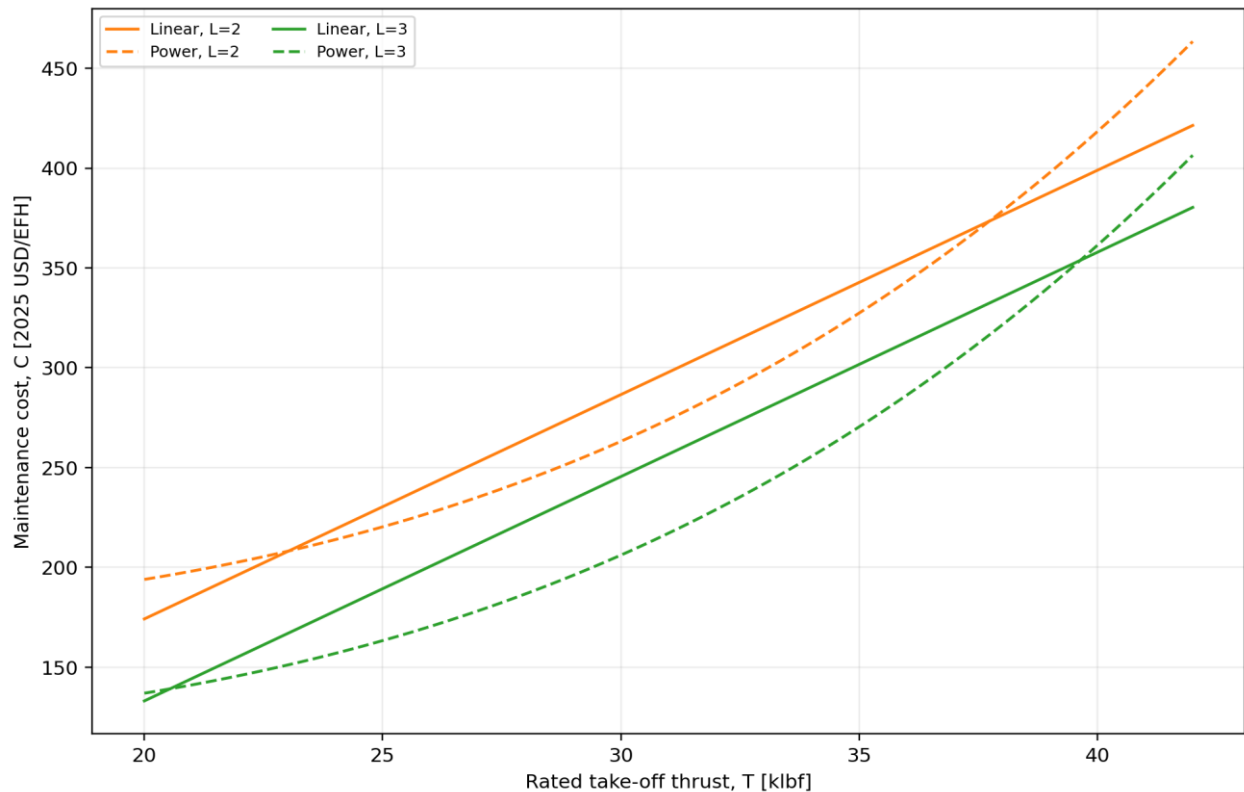


Figure 4.2 Small/medium engines: linear (solid) versus power-law (dashed) regression for $L = 2$ and 3, within the observed flight-cycle-length range

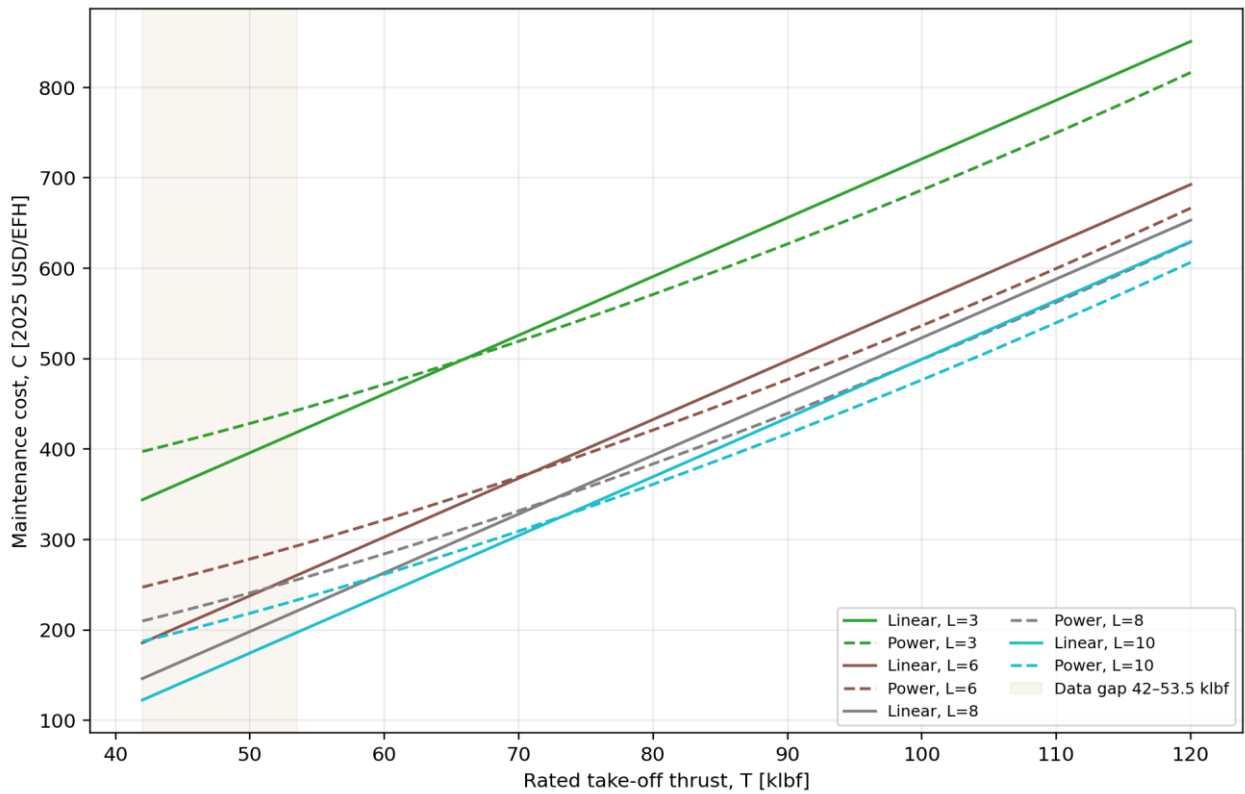


Figure 4.3 Large engines: linear (solid) versus power-law (dashed) regression for representative L within the calibrated range

4.5 Graphical Representation of the Power-Law Equation

Figure 4.4 presents the power-law model using the same calibration-range convention as Figure 4.1: small/medium engines are shown only for $L = 2$ and 3, while the large-engine branch is shown within $L = 1$ to 10. The 42 to 53.5 klbf observation gap is shaded.

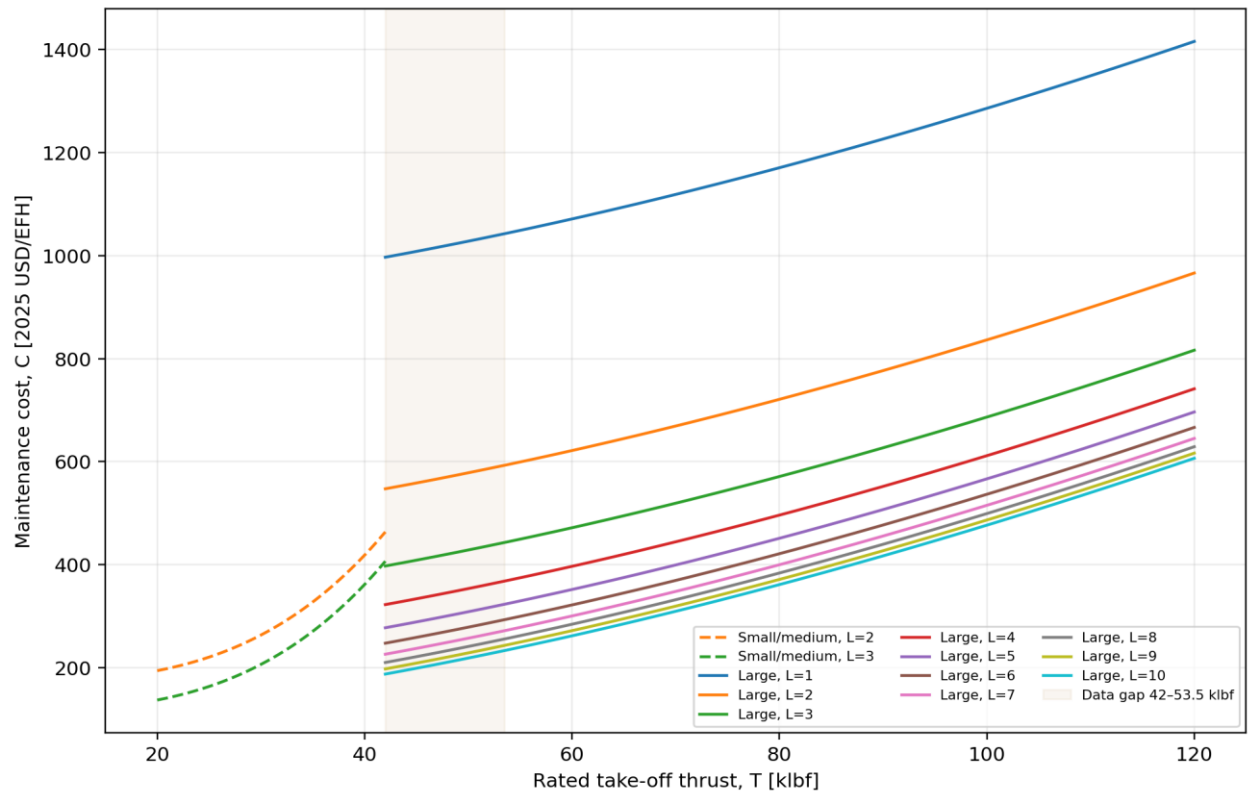


Figure 4.4 Engine maintenance cost versus thrust using the piecewise power-law model. Small/medium engines are shown for $L = 2$ and 3 only; large engines are shown for $L = 1$ to 10

5 Specific Engine Maintenance Cost, C/T

5.1 Motivation

Dividing maintenance cost by rated thrust gives the specific maintenance-cost measure C/T . This is not a normal maintenance-accounting quantity; it is an aircraft design diagnostic. Here it is derived from the recommended linear model so that the behavior of the preferred estimating equation can be interpreted directly.

5.2 Specific-Cost Equations

Dividing Equations (5a) and (5b) by T gives:

$$C/T = 11.241 + (-173.940 + 246.481/L)/T \quad (7a)$$

$$C/T = 6.498 + (-245.307 + 948.877/L)/T \quad (7b)$$

For a linear branch $C = a + bT + d/L$, the specific cost is $C/T = b + (a + d/L)/T$. Hence $\partial(C/T)/\partial T = -(a + d/L)/T^2$. The sign changes at $L_{crit} = -d/a$. For the small/medium branch $L_{crit} = 1.42$; for the large branch $L_{crit} = 3.87$. Thus C/T may decrease, remain nearly constant, or increase with thrust depending on flight-cycle length.

5.3 Graphical Interpretation

Figure 5.1 combines both branches of the recommended linear model using the same convention: dashed small/medium-engine curves and solid large-engine curves. Small/medium engines are shown only for $L = 2$ and 3 , within the observed range $1.2 \leq L \leq 3.0$. Large engines are shown for $L = 1$ to 10 . The shaded 42 to 53.5 klbf interval marks the observation gap.

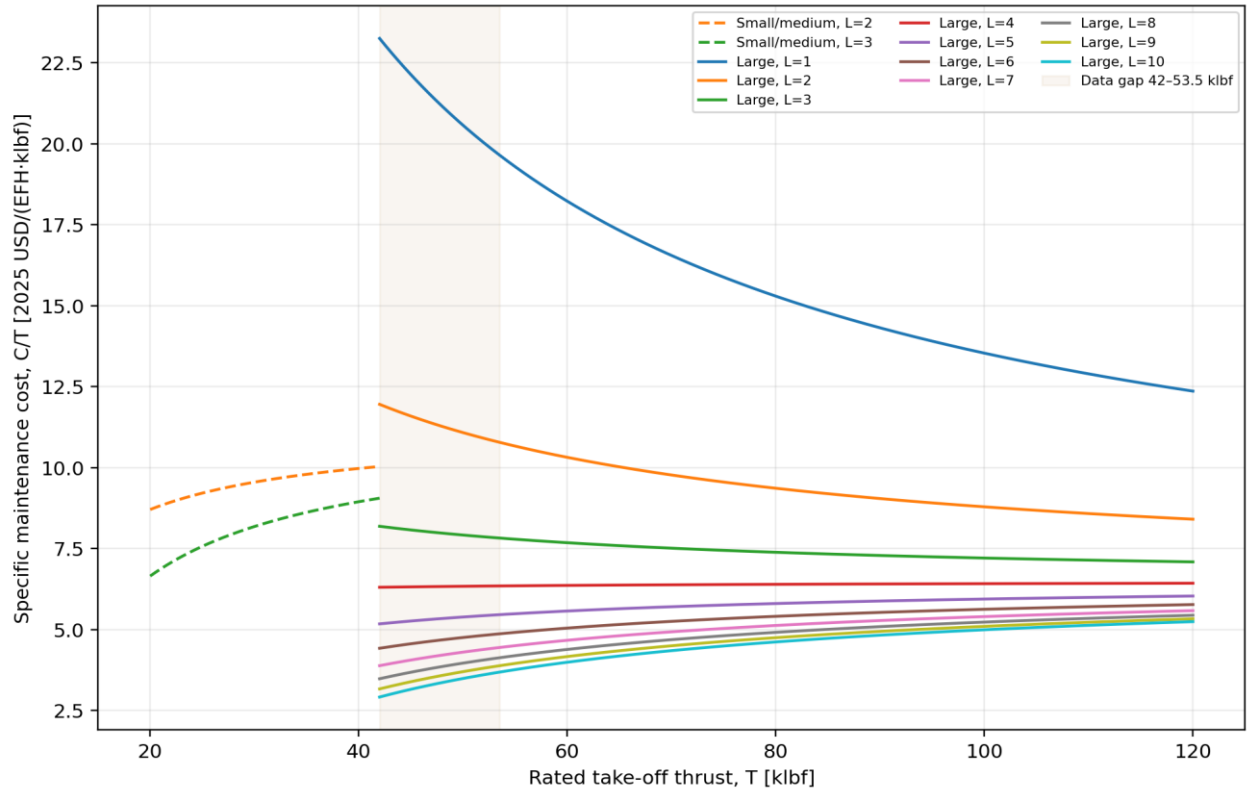


Figure 5.1 Specific engine maintenance cost C/T from the recommended linear equations. Small/medium engines are shown for $L = 2$ and 3 only; large engines are shown for $L = 1$ to 10

The figure shows that specific maintenance cost is not governed by thrust alone. For the small/medium branch the critical value $L_{cri} = 1.42$ lies near the lower end of the observed range; for most of its calibration range C/T increases with thrust under the fitted linear equation. For the large branch, C/T decreases with thrust for short cycles, is nearly independent of thrust around $L \approx 3.87$, and increases with thrust for longer cycles. These trends are empirical properties of the fitted equations and should not be extrapolated beyond their calibration domains.

5.4 Interpretation for Aircraft Design

For preliminary aircraft design, C/T should be used as a diagnostic rather than as the primary estimating equation. Aircraft-level engine maintenance cost is still obtained from C for each engine and multiplied by the number of engines. The C/T plot helps interpret whether a change in engine size is accompanied by an approximately proportional, sub-proportional or super-proportional maintenance-cost change. It also shows why cycles matter: the cycle-related contribution becomes especially important for short missions and smaller thrust levels.

6 Discussion

6.1 Plausibility of the Flight-Cycle Term

The $1/L$ dependence has a direct maintenance interpretation. Because $L = \text{EFH}/\text{EFC}$, a reserve associated with a flight cycle contributes D/L USD per flight hour. Same-engine observations at several L values support this form (see Appendix B). For example, CF6-80C2 repeated-L data can be represented very closely by $C = A + D/L$, with R^2 close to unity. This behavior provides stronger physical support for the L term than would a purely statistical multivariable fit.

6.2 Applicability, Extrapolation and Sample Size

The recommended equations are empirical correlations and should normally be used within, or close to, their calibration domains. The small/medium branch covers $23.76 \leq T \leq 41.7$ klbf and $1.2 \leq L \leq 3.0$; the large branch covers $53.5 \leq T \leq 112.65$ klbf and $1 \leq L \leq 10$. No observations lie between 41.7 and 53.5 klbf. Figures 4.1 to 5.1 therefore restrict the small/medium curves to $L = 2$ and 3 rather than visually presenting unsupported high- L extrapolations as ordinary model results. With $n = 35$ in total – and only $n = 10$ in the small/medium branch – the model is best regarded as an empirically supported preliminary-design relation, not a high-confidence universal law.

The negative constants in Equation (5) are regression intercepts and have no physical meaning. Within the intended thrust ranges the equations remain positive, including the mathematical limit $L \rightarrow \infty$. Extrapolation toward $T = 0$ is therefore neither required nor meaningful for the intended application.

6.3 Inflation and Cost Escalation

CPI-U is used to normalize dollar years because it is transparent, reproducible and available for every source year. Limited same-engine comparisons at later dates show that actual engine-MRO escalation can differ from general inflation because reliability, maturity, workscope, parts pricing and life-limited-part policy change with time. The available comparisons do not support one universal additional MRO escalation factor. Accordingly, no generic factor beyond CPI is included in the final equation.

6.4 Current Engine-MRO Environment and Cost Escalation

The dollar normalization in this note must not be confused with a forecast of current market prices. CPI-U removes general historical price-level differences so that observations from different years can be regressed consistently. Actual engine-MRO prices can move much faster than consumer inflation because of spare-parts shortages, material prices, labor rates, shop capacity, repair availability, OEM aftermarket policy and engine-specific durability problems. These effects change the commercial price of maintenance without necessarily changing the underlying thrust-and-cycle physics represented by the regression.

This distinction is particularly important in the present market. IATA reported in June 2026 that latest-generation single-aisle engine MRO was constrained by durability issues, spare-parts shortages, limited spare-engine availability and maintenance capacity; the association cited 648 GTF-powered aircraft grounded at the March 2025 peak while awaiting engine shop visits, spare engines or parts. IATA also estimated that wider aviation supply-chain problems cost airlines more than 11 billion USD in 2025, including about 3.1 billion USD in additional maintenance cost and 2.6 billion USD in excess engine leasing (IATA 2026a; IATA 2026b). These are system-level consequences and should not simply be added as a constant to Equation (5).

Independent MRO-industry survey evidence points in the same direction. Sargent (2026) reported that engine shop visits for many narrowbody operators regularly required 180 to 200 days or more from shop induction to completion, material-cost inflation remained elevated, and two-thirds of respondents said shop costs for newest-generation narrowbody engines were at least 21% above expectations (Sargent 2026). Such figures illustrate why a historical empirical reserve equation can underpredict a specific contemporary engine family during an abnormal supply-and-durability episode.

For preliminary aircraft design, Equation (5) should therefore be interpreted as a normalized structural estimate: thrust T represents engine size and associated maintenance material exposure; $1/L$ represents cycle consumption; the residual scatter absorbs technology, maturity and workscope differences. If a study requires present-day cash cost for a specific engine family, the regression should be supplemented by a transparent scenario factor or family-specific market information rather than modifying the thrust or L exponents. The present data did not justify one universal “MRO escalation factor” beyond CPI.

7 Application

7.1 Engine-Number Trade in Preliminary Aircraft Design

The maintenance cost model can be used in preliminary aircraft design to examine the effect of engine number when the required total installed thrust is approximately fixed. Let T_Σ be the total installed thrust and n the number of identical engines. The rated thrust per engine is then

$$T = \frac{T_\Sigma}{n} .$$

Within one branch of the recommended linear regression, the maintenance reserve of one engine is

$$C = a + bT + \frac{d}{L} .$$

For a fixed design mission, L is approximately fixed. The aircraft-level engine maintenance reserve per flight hour is obtained by multiplying the per-engine value by the number of engines. This is

$$C_{AC} = nC = n \left(a + b \frac{T_\Sigma}{n} + \frac{d}{L} \right) .$$

Rearrangement gives a particularly useful aircraft design relation

$$C_{AC} = bT_\Sigma + n \left(a + \frac{d}{L} \right) .$$

This relation applies directly only when all candidate engine sizes remain within the same regression branch. For fixed total thrust and fixed L , the first term is independent of engine number. The sensitivity to engine number is therefore

$$\frac{\partial C_{AC}}{\partial n} = a + \frac{d}{L} .$$

The sign changes at the critical flight-cycle length

$$L_{crit} = -\frac{d}{a} .$$

If $L < L_{crit}$, the term $a + d/L$ is positive and fewer engines reduce the modeled aircraft-level engine maintenance reserve. If $L > L_{crit}$, the term is negative and more engines reduce the modeled reserve. This result is equivalent to the specific-cost analysis based on C/T , because

$$\frac{C}{T} = b + \frac{a + d/L}{T}$$

and

$$\frac{d(C/T)}{dT} = -\frac{a + \frac{d}{L}}{T^2} .$$

The result is an interpretation of the empirical regression, not a general physical law for engine number. It must be used within the calibration limits and together with the other consequences of aircraft configuration.

7.2 Example 1: Aircraft of the Size of an Airbus A340

As a first illustrative trade, consider an aircraft requiring approximately 136 klbf total installed thrust. For a typical mission let's assume $L = 7$. A four-engine configuration is represented by four engines of 34 klbf each, whereas a twin-engine configuration is represented by two engines of 68 klbf each. This example is deliberately simple: total installed thrust and mission flight-cycle length are held constant so that only the modeled engine-maintenance consequence of engine number and engine size is compared.

For four engines of 34 klbf, the small/medium-engine regression gives

$$C_{34} = -173.940 + 11.241 \cdot 34 + \frac{246.481}{7} \approx 243.5 \frac{\text{USD}}{\text{EFH}} .$$

The aircraft-level value is therefore

$$C_{AC,4} = 4C_{34} \approx 974 \frac{\text{USD}}{\text{FH}} .$$

For two engines of 68 klbf, the large-engine regression gives

$$C_{68} = -245.307 + 6.498 \cdot 68 + \frac{948.877}{7} \approx 332.1 \frac{\text{USD}}{\text{EFH}} .$$

The corresponding aircraft-level value is

$$C_{AC,2} = 2C_{68} \approx 664 \frac{\text{USD}}{\text{FH}} .$$

The model therefore gives a reduction of approximately 310 USD/FH, or about 32%, for the twin-engine configuration relative to the four-engine configuration. This numerical result requires careful interpretation, because the two alternatives do not belong to the same regression branch.

7.3 Specific Cost and the Apparent Contradiction in Example 1

The specific maintenance cost C/T provides an additional way to examine the engine-number trade. For the small/medium branch at $L = 7$,

$$\frac{C_{small}}{T} = 11.241 + \frac{-173.940 + 246.481/7}{T} = 11.241 - \frac{138.729}{T}.$$

For $T = 34$ klbf this gives

$$\frac{C_{small}}{T} \approx 7.16 \frac{\text{USD}}{(\text{EFH} \cdot \text{klbf})}.$$

For the large-engine branch at the same L ,

$$\frac{C_{large}}{T} = 6.498 + \frac{-245.307 + 948.877/7}{T} = 6.498 - \frac{109.753}{T}.$$

For $T = 68$ klbf this gives

$$\frac{C_{large}}{T} \approx 4.88 \frac{\text{USD}}{(\text{EFH} \cdot \text{klbf})}.$$

At first sight this appears inconsistent with the derivative of C/T . The critical flight-cycle lengths are approximately $L_{crit} = 1.42$ for the small/medium branch and $L_{crit} = 3.87$ for the large branch. Since $L = 7$ exceeds both values, C/T increases with thrust within either branch. One might therefore expect the smaller engines to have the lower specific maintenance cost.

However, there is no algebraic contradiction. The statement that C/T increases with T applies within an individual regression branch. The comparison from 34 klbf to 68 klbf crosses from the small/medium regression to the large-engine regression. The two independently fitted branches have different coefficients; in particular, the thrust coefficient decreases from $b = 11.241$ to $b = 6.498$ USD/(EFH · klbf). The change of regression branch is sufficiently large to reverse the within-branch tendency.

The approximately 32% advantage of the twin in this example is therefore a model-dependent result and should not be interpreted as a general physical result that two larger engines intrinsically have lower maintenance cost than four smaller engines. Two further limitations reinforce this caution. First, $L = 7$ lies outside the observed L range of 1.2 to 3.0 for the small/medium branch. Second, the comparison crosses the observation gap between approximately 42 and 54 klbf. The example remains useful because it exposes both the intended use and the limitations of a piecewise preliminary-design regression.

7.4 Example 2: Aircraft of the Size of an Airbus A380

This second theoretical example avoids the branch-change complication. Consider an aircraft requiring approximately 300 klbf total installed thrust at $L = 7$. Four engines would each provide 75 klbf, whereas a twin-engine version would require approximately 150 klbf per engine. Both alternatives are evaluated with the large-engine regression. The 150-klbf case is intentionally an extrapolation beyond the calibration range, which ends at 112.65 klbf. It is also beyond the rated thrust of current commercial turbofans: for comparison, the GE9X is certified at approximately 105,000 lbf (GE Aerospace 2025) and the Trent XWB-97 at 97,000 lbf (Rolls-Royce 2018). The 150-klbf engine is therefore a hypothetical preliminary-design propulsion unit.

At $L = 7$, the large-engine regression becomes

$$C = -109.753 + 6.498T \quad .$$

For four engines of 75 klbf,

$$C_{75} = -109.753 + 6.498 \cdot 75 \approx 377.60 \text{ USD/EFH}$$

and

$$C_{AC,4} = 4C_{75} \approx 1510.39 \frac{\text{USD}}{\text{FH}} \quad .$$

For two hypothetical engines of 150 klbf,

$$C_{150} = -109.753 + 6.498 \cdot 150 \approx 864.95 \text{ USD/EFH}$$

and

$$C_{AC,2} = 2C_{150} \approx 1729.89 \frac{\text{USD}}{\text{FH}} \quad .$$

The twin therefore has a modeled maintenance reserve approximately

$$1729.89 \frac{\text{USD}}{\text{FH}} - 1510.39 \frac{\text{USD}}{\text{FH}} = 219.50 \frac{\text{USD}}{\text{FH}}$$

higher than the four-engine configuration. Relative to the four-engine value, the twin is about 14.5% more expensive; equivalently, the four-engine configuration is about 12.7% less expensive than the twin.

Unlike Example 1, this result can be anticipated directly from C/T . Since $L = 7 > L_{crit, large} = 3.87$, specific maintenance cost increases with thrust within the large-engine branch. Thus the 150-klbf engine must have a higher C/T than the 75-klbf engine:

$$\frac{C_{75}}{75} \approx 5.035 \frac{\text{USD}}{\text{EFH} \cdot \text{klbf}} ,$$

$$\frac{C_{150}}{150} \approx 5.766 \frac{\text{USD}}{\text{EFH} \cdot \text{klbf}} .$$

The general engine-number equation gives the same result even more directly. At $L = 7$,

$$a + \frac{d}{L} = -245.307 + \frac{948.877}{7} = -109.753 \frac{\text{USD}}{\text{EFH}} .$$

Changing from two to four engines therefore changes the aircraft-level reserve by

$$\Delta C_{AC} = (4 - 2) \left(-109.753 \frac{\text{USD}}{\text{FH}} \right) = -219.51 \frac{\text{USD}}{\text{FH}} .$$

The agreement between the direct calculation, the C/T interpretation, and the general engine-number equation makes this example a useful illustration of the regression in preliminary aircraft design. At the same time, the 150-klbf result should be treated with due caution because it is a substantial extrapolation.

7.5 From Few Engines to Distributed Propulsion

The engine-number equation raises the question whether its mathematical trend could be continued toward very large numbers of engines. Such an interpretation would connect the present discussion with distributed propulsion, where many propulsion units may be arranged along a wing. The turbofan maintenance regression itself must not be extrapolated in this manner: as n increases at fixed total thrust, $T = T_{\Sigma}/n$ tends toward zero and eventually leaves

the empirical thrust range entirely. The negative regression intercepts already indicate that the equations are not physical models in the limit $T \rightarrow 0$. Distributed electric propulsion is an additional special case because electric motors can have fundamentally different maintenance-cost scaling from turbofan engines.

Nevertheless, the geometric limit of a highly distributed propeller or fan installation is instructive. Assume that (1) every propulsion unit has a propeller or fan, (2) the propulsion units are placed side by side along the wing leading edge, (3) the available span b_w is fixed, (4) the propeller or fan disks may not overlap and may not extend over the wing tip, and (5) the complete span may be used, without additional restrictions from the fuselage or other installation details. Let D be the diameter of each of n equal propellers or fans and g the minimum clearance (gap) between adjacent disks. The span occupied by the propulsion system is then

$$nD + (n - 1)g = b_w .$$

Hence

$$D = \frac{b_w - (n - 1)g}{n} = \frac{b_w}{n} - g + \frac{g}{n} .$$

For a finite positive clearance g , an infinite number of propulsors is geometrically impossible. Positive diameter requires

$$b_w - (n - 1)g > 0 ,$$

or

$$n < 1 + \frac{b_w}{g} .$$

The idealized limiting case $g = 0$ is therefore useful for examining $n \rightarrow \infty$. In that case,

$$D = \frac{b_w}{n} .$$

The total propeller or fan disk area is

$$A_{disk,tot} = n \frac{\pi D^2}{4} = \frac{\pi b_w^2}{4n} .$$

Consequently,

$$\lim_{n \rightarrow \infty} A_{disk,tot} = 0 .$$

For fixed required total thrust, the corresponding disk loading $T_\Sigma / A_{disk,tot}$ tends to infinity. In ideal momentum theory, increasingly high disk loading requires increasingly high induced velocity and induced power. Thus the ideal propulsive efficiency tends toward zero in the

limiting case. Under the stated geometric assumptions, unlimited subdivision of propulsion is therefore not an aerodynamic optimum.

The opposite mathematical extreme is $n = 1$. For $g = 0$,

$$D = b_w$$

and

$$A_{disk,tot} = \frac{\pi b_w^2}{4},$$

which is the maximum disk area permitted by the deliberately simplified span constraint. This does not imply that one engine is an aircraft design optimum. Such an installation would normally be constrained by geometry, ground clearance, structure, fan or propeller tip speed, transmission, engine-out requirements, controllability, redundancy, certification, and other considerations.

The two limits therefore illustrate why engine number cannot be optimized from the maintenance regression alone. Neither maintenance cost nor propulsive efficiency provides a general argument for minimizing or maximizing engine number. The regression can support engine-number trades within an appropriate turbofan design space; aerodynamic, propulsive, structural, operational, safety, and installation effects must complete the aircraft-level trade. Distributed propulsion may exploit additional integration effects, but those effects and the maintenance scaling of electric propulsion systems lie outside the empirical basis of the present model.

8 Summary

Published civil-turbofan maintenance-reserve data were assembled and normalized to 2025 USD. The final data set contains 35 observations and covers approximately 23 to 113 klbf. The maintenance quantity is the planned reserve for shop visits and LLP replacement where separable. Flight-cycle length is represented by $L = \text{EFH}/\text{EFC}$, giving a physically interpretable cycle term proportional to $1/L$.

The recommended preliminary-design model is a piecewise linear regression. For small/medium engines,

$$C = -173.940 + 11.241 T + 246.481 / L ,$$

and for large engines,

$$C = -245.307 + 6.498 T + 948.877 / L .$$

The small/medium branch is based on 10 observations over $L = 1.2$ to 3.0 ; the large-engine branch is based on 25 observations over $L = 1$ to 10 . Their coefficients of determination are $R^2 = 0.581$ and 0.858 , respectively, and the combined RMSE is 67.24 USD/EFH. The limited small/medium data and the observation gap between 41.7 and 53.5 klbf are important limitations.

Power-law alternatives provide sensitivity checks but do not improve the model overall. The piecewise linear model is therefore preferred for its statistical performance, simplicity and direct interpretability. Dividing the equations by thrust gives the specific engine maintenance cost, C/T , and reveals a critical flight-cycle length at which its dependence on thrust changes sign. At fixed total installed thrust, the equations can also be reformulated in terms of engine number. This permits preliminary four-versus-two-engine maintenance-cost trades while also showing why extrapolation towards distributed propulsion lies outside the empirical basis of the model.

9 Conclusions and Recommendations

The analysis shows that planned turbofan engine maintenance reserve can be represented for preliminary aircraft design by a compact empirical relation using rated take-off thrust and engine flight-cycle length. The recommended piecewise linear model provides the best balance of fit quality, simplicity and interpretability for the available data. The explicit $1/L$ term captures the strong influence of cyclic operation, while the thrust term represents the increase in maintenance burden associated with engine size. The equations should be applied within their calibration ranges, particularly because the small/medium-engine data are limited and an observation gap exists between 41.7 and 53.5 klbf.

An important aircraft-design implication is that the maintenance-cost consequences of engine sizing and engine number cannot be inferred from thrust alone. The specific maintenance cost C/T may increase or decrease with engine thrust depending on flight-cycle length, and a change in engine number may also move the design from one regression branch to another. Nevertheless, the regression provides a transparent means of quantifying these effects and of understanding their causes. The examples demonstrate the value of such isolated analyses in preliminary design: they reveal individual physical and economic trends that may be difficult to recognize in the output of a comprehensive aircraft-design calculation.

Further work should extend the database with independent and more recent engine maintenance observations, particularly for small/medium engines and for the present observation gap and should investigate additional explanatory variables where suitable data become available. From an aircraft-design perspective, the engine-number investigation should be extended beyond maintenance cost, initially to propulsion efficiency and fuel consumption and subsequently to engine mass, installation, aerodynamics, structural effects, reliability and operational consequences. Such isolated investigations are valuable for establishing and understanding individual cause-and-effect relationships. Ultimately, however, the interactions between these effects require assessment in an integrated aircraft design tool. The two approaches are complementary: transparent isolated models provide understanding and checks on trends, while integrated design calculations account for the interdependencies required for an overall aircraft-level assessment.

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Appendix A – Regression Data

Table A.1 lists the 35 observations used for the regression. For each source-derived variable, the adjacent p. column gives the printed page number in the cited source. C_y denotes maintenance cost in source year y ; C_{2025} is the corresponding cost normalized to 2025 USD. Where a regression input represents several engine variants, representative rated take-off thrust is the arithmetic mean of the ratings of the variants explicitly represented by that observation. “calc.” indicates a value calculated from data reported in the source; ordinary rounding is not identified as a calculation. To save space, AC in the Source column abbreviates the corporate author AIRCRAFT COMMERCE; for example, AC 2007a corresponds to AIRCRAFT COMMERCE, 2007a in the List of References. The calculation of C_{2025} is common to all observations and is described below the table.

Table A.1 Observation-level regression data and 2025-dollar normalization.

Engine/group	T [klbf]	p.	L	p.	Year	C_y [USD/EFH]	p.	C_{2025} [USD/EFH]	Source
CFM56-5A	24.25	9	1.2	26	2007	223.0	26	346.3	AC 2007a; T calc.
CFM56-5B high	31.00	9	1.8	26	2007	131.0	26	203.4	AC 2007a; T calc.
CFM56-5B low	24.56	9	1.8	26	2007	126.0	26	195.6	AC 2007a; T calc.
V2522/24-A5	23.76	12	1.9	30	2008	151.0	30	225.8	AC 2008a; T calc.
V2527-A5	24.80	12	1.9	30	2008	192.0	30	287.1	AC 2008a
V2530/33-A5	30.75	12	1.9	30	2008	208.0	30	311.0	AC 2008a; T calc.
PW2037 RTC	38.25	13	3.0	26	2008	236.7	26	353.9	AC 2008b; C calc.
PW2000 non- RTC	39.98	13	3.0	26	2008	266.7	26	398.7	AC 2008b; T, C calc.
RB211-535E4	40.10	13	3.0	26	2008	237.2	26	354.6	AC 2008b; C calc.
PW2040 RTC	41.70	13	3.0	26	2008	246.5	26	368.6	AC 2008b; C calc.
CF6-80C2A2	53.50	8	3.0	30	2006	220.0	30	351.3	AC 2006
PW4052/56	54.48	20	3.0	28	2007	190.0	28	295.0	AC 2007b; T calc.
PW4056	56.75	20	8.0	28	2007	149.0	28	231.4	AC 2007b
PW4158	58.00	20	1.5	28	2007	563.0	28	874.2	AC 2007b
CF6- 80C2B1F	58.09	8	7.0	30	2006	160.0	30	255.5	AC 2006
CF6- 80C2A3/A5	60.75	8	1.0	30	2006	680.0	30	1085.9	AC 2006; T calc.
CF6- 80C2A3/A5	60.75	8	2.0	30	2006	353.0	30	563.7	AC 2006; T calc.
CF6- 80C2A3/A5	60.75	8	3.0	30	2006	245.0	30	391.3	AC 2006; T calc.
CF6- 80C2A3/A5	60.75	8	4.0	30	2006	210.0	30	335.4	AC 2006; T calc.
CF6- 80C2B6/B7	60.80	8	6.0	30	2006	187.0	30	298.6	AC 2006
PW4060/62	61.00	20	7.0	28	2007	165.0	28	256.2	AC 2007b; T, C calc.

Engine/group	T [klbf]	p.	L	p.	Year	C _y [USD/EFH]	p.	C ₂₀₂₅ [USD/EFH]	Source
CF6-80C2D1F	61.96	8	7.0	30	2006	180.0	30	287.4	AC 2006
CF6-80E1	67.90	42	3.0	52	2008	318.0	52	475.5	AC 2008c; T calc.; see note
CF6-80E1	67.90	42	6.0	52	2008	260.0	52	388.8	AC 2008c; T calc.
CF6-80E1	67.90	42	8.0	52	2008	237.0	52	354.4	AC 2008c; T calc.
PW4168	68.60	42	3.0	52	2008	345.0	52	515.9	AC 2008c
PW4168	68.60	42	6.0	52	2008	261.0	52	390.3	AC 2008c
PW4168	68.60	42	8.0	52	2008	228.0	52	340.9	AC 2008c
Trent 772	71.10	42	3.0	52	2008	462.0	52	690.8	AC 2008c
Trent 772	71.10	42	6.0	52	2008	266.0	52	397.8	AC 2008c
Trent 772	71.10	42	8.0	52	2008	222.0	52	331.9	AC 2008c
GE90 standard	84.28	44	6.0	52	2008	408.0	52	610.1	AC 2008c; T calc.
GE90 standard	84.28	44	8.0	52	2008	370.0	52	553.3	AC 2008c; T calc.
GE90-110/115	112.65	44	8.0	53	2008	353.0	53	527.8	AC 2008c; T calc.
GE90-110/115	112.65	44	10.0	53	2008	309.0	53	462.0	AC 2008c; T calc.

Calculated and Representative Values in Table A.1

Rows 1 to 3

Representative CFM56 thrusts: $T(\text{CFM56-5A}) = (26.5 + 25.0 + 23.5 + 22.0)/4 = 24.25$ klbf; $T(\text{high}) = (32 + 31 + 30)/3 = 31.00$ klbf; $T(\text{low}) = (27 + 27 + 23.5 + 22 + 23.3)/5 = 24.56$ klbf. Row 1 uses the source's planned reserve of 223 USD/EFH; the higher value including heavy unscheduled maintenance is excluded.

Rows 4 and 6

$T(\text{V2522/24-A5}) = (23.04 + 24.48)/2 = 23.76$ klbf; $T(\text{V2530/33-A5}) = (29.90 + 31.60)/2 = 30.75$ klbf.

Rows 7 to 10

Planned cost values are calculated from the shop-visit and LLP quantities reported by the source: PW2037 RTC: $(167 + 173)/2 + 200/3 = 236.67$ USD/EFH; PW2000 non-RTC: $200 + 200/3 = 266.67$ USD/EFH; RB211-535E4: $(171 + 180)/2 + 185/3 = 237.17$ USD/EFH; PW2040 RTC: $(178 + 189)/2 + 189/3 = 246.50$ USD/EFH. For PW2000 non-RTC, $T = (38.25 + 41.70)/2 = 39.975 \approx 39.98$ klbf.

Row 12

$T(\text{PW4052/56}) = (52.20 + 56.75)/2 = 54.475 \approx 54.48$ klbf.

Rows 16 to 19

$T(\text{CF6-80C2A3/A5}) = (60.2 + 61.3)/2 = 60.75$ klbf.

Row 21

$$T(\text{PW4060}/62) = (60 + 62)/2 = 61.00 \text{ klbf}; C = (160 + 170)/2 = 165 \text{ USD/EFH}.$$

Rows 23 to 25

$T(\text{CF6-80E1}) = (65.8 + 69.8 + 68.1)/3 = 67.90 \text{ klbf}$. For $L = 3$, Aircraft Commerce (2008c, p. 52) gives 318 USD/EFH in the summary table, whereas the accompanying text gives 327 USD/EFH; the stated components also give $204 + 370/3 = 327.3 \text{ USD/EFH}$. The regression uses the tabulated value 318 consistently with Table A.1. For $L = 6$ and 8, the tabulated values 260 and 237 USD/EFH are consistent with the stated components: $203 + 343/6 = 260.2$ and $194 + 343/8 = 236.9 \text{ USD/EFH}$.

Rows 32 to 33

$$T(\text{GE90 standard}) = (76 + 77 + 84.7 + 90 + 93.7)/5 = 84.28 \text{ klbf}.$$

Rows 34 to 35

$$T(\text{GE90-110}/115) = (110 + 115.3)/2 = 112.65 \text{ klbf}.$$

Inflation Normalization

Historical maintenance costs are converted to constant 2025 USD using CPI-U, U.S. city average, All items, annual average, not seasonally adjusted. The index uses 1982 to 1984 = 100 as its reference base. Thus, 201.600 in 2006 represents 2.016 times the index reference price level. The absolute base does not affect the conversion because only the ratio of two index values is used. Table A2 has list the values extracted from BLS 2008, BLS 2009, and BLS 2026.

Table A.2 Values of the Consumer Price Index (CPI) from BLS 2008, BLS 2009, and BLS 2026.

Source year y	CPI-Uy	CPI-U2025	Factor = CPI-U2025 / CPI-Uy
2006	201.600	321.943	1.59694
2007	207.342	321.943	1.55271
2008	215.303	321.943	1.49530

$$F2006 = 321.943 / 201.600 = 1.59694; F2007 = 321.943 / 207.342 = 1.55271; F2008 = 321.943 / 215.303 = 1.49530.$$

For every observation, $C2025 = C_y \cdot (\text{CPI-U2025} / \text{CPI-Uy})$.

Example for Row 11: $C2025 = 220 \cdot (321.943 / 201.600) = 351.33 \approx 351.3 \text{ USD/EFH}$.

Appendix B – Repeated-L Plausibility Checks

Repeated-L observations provide a direct check of the functional dependence on flight-cycle length without changing engine family. For the CF6-80C2A3/A5, total reserve observations at $L = 1, 2, 3$ and 4 are represented by

$$C_{total} = 40.2 + \frac{637.0}{L} \quad (R^2 = 0.9985) \quad (\text{B.1})$$

and planned shop reserve by

$$C_{shop} = 31.3 + \frac{464.5}{L} \quad (R^2 = 0.9960) \quad (\text{B.2})$$

These repeated-L fits support the use of $1/L$ as the mission-severity variable in the final regression. Similar behavior was found for Trent 700 repeated-L data, with R^2 values close to 0.998 to 1.000 depending on the life-limited-part case. These checks are used as physical plausibility evidence rather than as additional independent observations in the 35-point regression.