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Turbofan LTO Fuel Cost and NOx under Indian and US Price Scenarios

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Abstract

This study examines fuel expenditure associated with differences in turbofan oxides of nitrogen (NOx) emissions during the reference landing-and-take-off (LTO) cycle. The March 2026 ICAO Aircraft Engine Emissions Databank supplied 504 eligible records. Matching manufacturer, model, rated thrust and test-engine category, while retaining distinct documented combustors, yielded 52 comparisons involving 77 records. Fuel expenditure was calculated using quotes for four Indian cities, US Gulf Coast spot prices and dated INR/USD rates from April 2024 to April 2026, assuming a fuel density of 0.800 kg/L. Lower reported NOx coincided with lower fuel use in 26 comparisons, equal fuel use in 18 and higher fuel use in eight. Reconstruction from mode-level data changed five classifications. An illustrative historical PW4164 contrast combined 55 kg more fuel with 5.082 kg less NOx per LTO. Mean additional expenditure per kilogram of lower NOx was USD 8.01 under US quotes and USD 13.69–15.23 across Indian city quotes. Different commercial price bases limit direct country comparisons. These results support reference-cycle accounting and show sensitivity to source reconstruction, without establishing a general fuel-cost penalty from NOx reduction.

Keywords: turbofan engines; landing-and-take-off cycle; NOx emissions; fuel expenditure; certification records; price scenarios.

1. Introduction

Fuel expenditure and nitrogen oxides (NOx) are related through combustion, but they measure different aspects of engine performance. Fuel use determines the financial requirement of a specified operating cycle. NOx mass describes an emissions output whose air-quality consequences also depend on location, atmospheric chemistry and exposure. Airport pollution includes aircraft exhaust, ground equipment and road traffic, so an engine-level comparison addresses only part of the emissions problem [1].

A uniform fuel penalty for lower NOx cannot be assumed. Kyprianidis and Dahlquist [2] found that the relationship between energy efficiency and NOx depended on combustor architecture and on whether efficiency improved through thermal or propulsive changes. Certification records can reveal contrasts between documented configurations, but they cannot isolate these mechanisms without additional performance and test information.

Operational changes provide a separate route to reducing emissions. Reduced-thrust takeoff and single-engine taxiing can lower fuel consumption and pollutant emissions under suitable operating conditions [3]; [4]. These findings concern procedures applied to aircraft. The present study instead compares engine records under a common reference cycle, without assuming that the configurations can be substituted on a particular aircraft.

The financial and environmental questions also need separate accounting. Miller et al. [5] evaluated aviation NOx regulation using fuel costs and environmental damages. Skowron et al. [6] assessed climate consequences of fuel and NOx changes. Neither question can be answered by fuel expenditure alone: a monetary slope derived from reference-cycle fuel use excludes atmospheric responses, health effects and most implementation costs.

Activity-based inventories require information beyond certification parameters. Lang et al. [7] combined operational timing and flight trajectories in a Chinese LTO inventory. Applying prices from India and the United States to identical engine records serves a narrower purpose: it values the same physical quantities under different quoted prices. It does not estimate either country's fleet emissions.

Fukui and Miyoshi [8] examined fuel-price and taxation effects using US airline data. Their behavioural analysis differs from the fixed-quantity calculation here. In this study, price changes scale expenditure while engine fuel use and NOx remain fixed. That restriction permits a transparent financial comparison without estimating an airline response to prices.

The study uses the March 2026 ICAO Aircraft Engine Emissions Databank and observed fuel-price scenarios from April 2024 to April 2026. It examines whether lower reported NOx accompanies lower, equal or higher fuel use within strictly matched records, how expenditure changes across four Indian city quotes and a US Gulf Coast quote, and how the findings respond to reconstruction and alternative matching and price assumptions.

The intended contribution is an auditable comparison of certification records and their price sensitivity. Record identity, configuration information and source totals remain visible. The analysis does not identify a causal combustor effect or recommend an engine replacement. Differences between domestic Indian quotes and US wholesale spot prices also prevent interpretation as a harmonised comparison of airline procurement costs.

2. Literature review

The literature separates three questions relevant to this analysis: what determines engine emissions, how reference parameters translate to actual operations, and how physical emissions acquire an economic or environmental value. Evidence from one level helps interpret the others, but it does not remove their different data requirements.

2.1 Engine operating conditions and measured emissions

Harlass et al. [9] measured NOx during ground and flight tests of an A350 with Trent XWB-84 engines. Emission indices increased with combustion temperature, pressure and fuel flow; the tested switch to 100% sustainable aviation fuel produced no measurable NOx-index change. Li et al. [10], using aircraft exhaust plumes under real operating conditions, reported substantial variation in engine-specific nitric oxide emission factors. These studies support retaining engine identity and operating conditions rather than treating fuel consumption as a sufficient predictor of emissions.

The measurement basis matters when comparing those findings with certification data. Li et al. [10] measured nitric oxide and total particle number, whereas certification reporting can concern total NOx and non-volatile particles. Such quantities are not interchangeable. A difference between them cannot establish a databank error without reconciling species, operating conditions and units.

Trivanovic and Pratsinis [11] found opposing soot and nitric oxide responses when downstream air injection was repositioned in a laboratory spray burner. This provides evidence about local combustion mechanisms, but not the fuel requirement of a certified turbofan cycle. Alongside the architecture-dependent results of Kyprianidis and Dahlquist [2], it explains why a documented combustor contrast is scientifically relevant while remaining insufficient for causal attribution.

Configuration-specific matching therefore narrows the comparison without creating a controlled experiment. Pressure ratio, test history and other engine characteristics can still differ. The defensible output is a record contrast with stated conditions and exclusions.

2.2 Reference-cycle calculations and operational fuel estimation

Wen et al. [12] modelled varying LTO activity and time in mode at Chinese airports. Lang et al. [7] used operational timing and trajectories to construct a four-dimensional inventory. Both approaches demonstrate why fixed durations and observed airport activity answer different questions. Their use of modelled timing where observations were unavailable also requires distinguishing measured inputs from supplemented estimates.

Knacker et al. [13] compared taxi fuel models using Frankfurt Airport movement and airline fuel records. Machine-learning models improved prediction within that empirical evaluation. The study's value for the present design is the additional operational evidence it uses; its prediction performance is not a correction factor that can be transferred to the global certification sample.

Teoh et al. [14] combined trajectories, aircraft–engine information, performance models and meteorological data in the GAIA inventory for 2019–2021. Public inventory outputs make activity-based research possible, although public access to outputs does not imply unrestricted access to every construction input. A certification-record assessment needs fewer inputs and can be reproduced, provided that it retains its reference-cycle scope.

These studies locate the boundary between standardised comparisons and realised savings. To estimate an airline or airport outcome, engine parameters must be linked to the applicable aircraft, observed operations and relevant fuel purchasing arrangements.

2.3 Environmental consequences and the interpretation of cost

Eastham et al. [15] found that aviation's air-quality effects included a broad ozone response to NOx, with estimated health consequences sensitive to exposure-response assumptions. A kilogram difference in reference-cycle NOx therefore cannot be valued as an avoided health effect without atmospheric and exposure modelling.

Climate valuation adds dependence on the chosen metric and time horizon. Megill et al. [16] compared alternative metrics for aviation non-CO2 effects, while Prather et al. [17] assessed uncertain climate trade-offs involving additional CO2 and reduced non-CO2 effects. These approaches evaluate climate response, not the fuel-only expenditure slope calculated here.

The distinction precludes a simple environmental verdict. Additional fuel use does not establish that a lower-NOx configuration is undesirable, and lower NOx does not establish that its environmental benefits offset additional fuel. Both judgements require information outside the present accounting boundary.

2.4 Implications for the present study

The reviewed research supports an accounting question that can be answered with publicly obtainable certification parameters and quoted prices: how documented fuel and NOx differences translate into reference-cycle expenditure under dated scenarios. This study tests that relationship through strict record matching and reconstruction rather than claiming an unverified absence of earlier research.

The analysis asks how fuel and NOx vary across matched records, how price scenarios change expenditure, and which positive fuel increments persist when calculation and selection rules change. It also tests the mathematical invariance of fuel ranking under a common positive price. These questions connect propulsion data with financial sensitivity while keeping operational savings and environmental valuation outside the estimated results.

3. Methods for engine records and LTO calculations

The unit of engine analysis is the databank UID. Fuel mass and NOx mass are evaluated per engine per reference LTO cycle. Observed fuel prices then generate conditional expenditures for those fixed quantities. The

engine and price files were archived on 10 October 2026; the engine source is the March 2026 edition and the common price window is April 2024–April 2026 [18]; [19]; [20]; [21].

3.1 Sample selection and comparison groups

The primary sample comprises TF or MTF records with rated thrust above 26.7 kN, data status C or C/R, positive published fuel totals and nonnegative published NOx totals. Superseded records and records explicitly marked out of service are excluded. A missing engine-status value is not interpreted as evidence of active service. Excluding R-only records is an analyst-defined study choice, not a claim that all revised data are invalid. Non-superseded R-only records are examined separately in a documented sensitivity analysis.

UIDs are retained throughout. Text matching trims leading and trailing spaces, collapses repeated internal whitespace and ignores case; original labels remain in the archive. Primary configuration eligibility requires a nonblank combustor description and no unresolved duplicate combination of manufacturer, model, combustor, rated thrust and test-engine category. Ambiguous configurations are excluded rather than assigned a representative UID. Records are neither averaged nor deduplicated on model name alone.

The baseline compares all unique unordered pairs with identical normalised manufacturer and model labels, exact rated thrust and the same test-engine category, but different documented combustor descriptions. Broader comparisons retain the manufacturer, exact model label and test category and allow pairwise thrust distances of 2%, 5% or 10%. These are sensitivities, not the baseline. The relative distance uses the smaller rating:

Equation 1. Relative thrust distance between records a and b

$$r_{\mathrm{ab}} = \frac{|T_{\mathrm{a}} - T_{\mathrm{b}}|}{\min(T_{\mathrm{a}}, T_{\mathrm{b}})}$$

Equation 2. Analyst-defined pairwise tolerances

$$r_{\mathrm{ab}} \leq \tau; \;\; \tau \in \{0.02, 0.05, 0.10\}$$

T denotes rated thrust and r is dimensionless. The tolerances are analyst-defined pairwise rules; they do not place records around a prespecified family reference rating. Broad thrust bands describe the sample only. Common aircraft applicability has not been independently verified, so every pair is interpreted as a certification-record comparison.

3.2 Reconstruction of fuel and NOx

Reference durations are 42 s for takeoff, 132 s for climb-out, 240 s for approach and 1560 s for idle. Fuel flow is multiplied by duration in each mode. For NOx, that mode fuel mass is also multiplied by its emission index [22]; [7].

Equation 3. Reference mode durations in seconds

$$(t_{\mathrm{TO}}, t_{\mathrm{CO}}, t_{\mathrm{AP}}, t_{\mathrm{ID}}) = (42, 132, 240, 1560)$$

Equation 4. Reconstructed cycle fuel mass

$$F_{\mathrm{i}} = \sum_{m} f_{\mathrm{im}} t_{\mathrm{m}}$$

Equation 5. Reconstructed cycle NOx mass

$$N_{\mathrm{i}} = \sum_{m} f_{\mathrm{im}} t_{\mathrm{m}} EI_{\mathrm{im}}$$

i identifies a UID and m identifies one of the four operating modes. Fuel flow f is in kilograms per second, time t is in seconds, and the emission index EI is in grams of NOx per kilogram of fuel. F is kilograms of fuel per engine per cycle, and N is grams of NOx per engine per cycle. Products use the unrounded source observations where available; rounding is applied only to displayed outputs.

Equation 6. Conversion of cycle NOx to kilograms

$$N_{\mathrm{i,kg}} = \frac{N_{\mathrm{i}}}{1000}$$

NOx is divided by 1000 when it enters an expenditure-per-kilogram calculation. The reference cycle describes certification accounting; it does not reproduce actual airport taxi times, airline schedules or cruise emissions.

3.3 Preservation and reconciliation of source totals

Published cycle totals remain the primary accounting inputs. Reconstructed totals are retained in separate columns and used for reconciliation and sensitivity analyses. For fuel and NOx, the audit reports both the absolute difference and its percentage relative to the published total.

Equation 7. Absolute reconciliation difference

$$A_{\mathrm{Y,i}} = \left|Y_{\mathrm{i,rec}} - Y_{\mathrm{i,pub}}\right|$$

Equation 8. Percentage reconciliation difference

$$D_{\mathrm{Y,i}} = 100\frac{A_{\mathrm{Y,i}}}{Y_{\mathrm{i,pub}}}$$

Y denotes either fuel F or NOx N; rec and pub identify reconstructed and published values. The percentage is calculated only when the published total is positive. For a zero published NOx total, the absolute difference is reported and the percentage is marked undefined.

An absolute percentage discrepancy above 2% is an analyst-defined reconciliation flag. Published totals remain unchanged; discrepancies are not treated as confirmed manufacturer errors. The flagged UIDs and missing metadata are reported in Results.

Final test dates identify historical coverage and define a known-date sensitivity from 2023 onward. Missing dates remain missing. The databank edition year is not assigned to undated tests.

3.4 Price alignment and unit conversion

For each Indian effective date, the date-aligned specification selects the earliest date on or after that date, within the same month, on which both the US fuel quote and the exchange-rate observation are available. The Indian effective date and the actual US and exchange-rate dates are retained. If no joint date exists, the scenario is unavailable. This procedure selects an observed quote; it neither fills missing observations nor treats the Indian quote as a monthly mean.

Let P be the Indian quote in INR per kilolitre, Q the US quote in USD per US gallon, X the exchange rate in INR per USD, and ρ the assumed density in kilograms per litre. One US gallon is 3.785411784 litres. Indian and US prices are converted to price per kilogram as follows.

Equation 9. Indian price in INR per kilogram

$$p_{\mathrm{India,INR}} = \frac{P}{1000\rho_{\mathrm{IN}}}$$

Equation 10. Indian price in USD per kilogram

$$p_{\mathrm{India,USD}} = \frac{P}{1000\rho_{\mathrm{IN}}X}$$

Equation 11. US price in USD per kilogram

$$p_{\mathrm{US,USD}} = \frac{Q}{3.785411784\rho_{\mathrm{US}}}$$

Equation 12. US price in INR per kilogram

$$p_{\mathrm{US,INR}} = \frac{QX}{3.785411784\rho_{\mathrm{US}}}$$

The central density is 0.800 kg/L. Sensitivities use 0.775 and 0.840 kg/L, corresponding to the stated Jet A-1 density specification bounds at 15 °C [23]. They are assumed values, not delivery measurements. Indian and US densities also vary separately. Because temperature-normalisation of the quoted volumes has not been established for both price sources, these cases describe conversion assumptions rather than measured physical uncertainty.

An alternative specification uses the arithmetic mean of the available daily US quotes within each month. When the monthly price is expressed in INR, each daily US quote is converted using its same-day exchange rate before averaging.

Equation 13. Monthly US price in INR per kilogram

$$\bar{p}_{\mathrm{US,INR,M}} = \frac{1}{n_{\mathrm{M}}} \sum_{d \in D_{\mathrm{M}}} \frac{Q_{\mathrm{d}} X_{\mathrm{d}}}{3.785411784\rho_{\mathrm{US}}}$$

D_M is the set of days in month M with both price and exchange-rate observations, and n_M is the number of those days. The monthly USD specification averages Q over its documented set of available daily observations and divides by the gallon-to-litre factor and assumed US density. The product of separately averaged price and exchange-rate series is not substituted for the mean of daily converted prices unless explicitly labelled an approximation. Original-currency expenditures are presented alongside converted scenario expenditures.

3.5 Nondominated records and incremental expenditure

For engine i under price basis s and matched observation t, cycle fuel expenditure is the primary published cycle fuel requirement multiplied by the scenario price per kilogram. The reconstructed fuel total is substituted only in the corresponding sensitivity case.

Equation 14. Fuel expenditure per engine per reference cycle

$$C_{\mathrm{i,s,t}} = F_{\mathrm{i}} p_{\mathrm{s,t}}$$

C is expenditure in the currency of p, s identifies an Indian city or US quote basis, and t identifies the matched price observation. Currency conversion changes the accounting scenario; it does not imply country differences in fuel use or NOx emissions.

Within each strict comparison group, a record is dominated when another requires no greater fuel and emits no greater NOx, with a strict reduction in at least one quantity. Classification uses the stored published numbers. The implementation treats pairwise differences within 10^{-9} kg as numerical equality; this computational tolerance is not a measurement-error bound. A formal rounding-sensitive classification has not been completed. The nondominated set describes certification records rather than a thermodynamic design frontier.

Equation 15. Condition for record a to dominate record b

$$F_{\mathrm{a}} \leq F_{\mathrm{b}}, \qquad N_{\mathrm{a}} \leq N_{\mathrm{b}}; \;\; (F_{\mathrm{a}} < F_{\mathrm{b}} \text{ or } N_{\mathrm{a}} < N_{\mathrm{b}})$$

Equation 16. A common positive price preserves the fuel ranking

$$p > 0\text{: } F_{\mathrm{a}} \leq F_{\mathrm{b}} \;\Leftrightarrow\; pF_{\mathrm{a}} \leq pF_{\mathrm{b}}$$

Because multiplication by the same positive price preserves fuel ordering, fuel-cost rankings and fuel-cost–NOx nondominated membership do not change across common-price scenarios. Prices change expenditure and pairwise trade-off slopes.

For a record a with lower NOx but higher fuel requirement than record b, the incremental expenditure is divided by the reduction in NOx expressed in kilograms.

Equation 17. Additional scenario fuel expenditure

$$\Delta C_{\mathrm{ab,s,t}} = p_{\mathrm{s,t}}(F_{\mathrm{a}} - F_{\mathrm{b}})$$

Equation 18. Reduction in NOx mass in kilograms

$$\Delta N_{\mathrm{ab,kg}} = \frac{N_{\mathrm{b}} - N_{\mathrm{a}}}{1000}$$

Equation 19. Incremental expenditure per kilogram of avoided NOx

$$K_{\mathrm{ab,s,t}} = \frac{\Delta C_{\mathrm{ab,s,t}}}{\Delta N_{\mathrm{ab,kg}}} = \frac{p_{\mathrm{s,t}}(F_{\mathrm{a}} - F_{\mathrm{b}})}{\frac{N_{\mathrm{b}} - N_{\mathrm{a}}}{1000}}$$

K is conditional fuel expenditure per kilogram of lower reference-cycle NOx. Ratios are reported only for positive fuel increments when the NOx reduction is at least max(0.100 kg, 0.01 × the higher-NOx total). All pairs remain in the classification table. This analyst-defined screen limits very small denominators; it is not a regulatory threshold or a calibrated precision bound. Lower fuel with lower or equal NOx is reported as dominance, and zero NOx differences do not yield a ratio.

3.6 Sensitivity analyses and scope of inference

Completed sensitivities reconstruct both cycle totals, exclude the six fuel flags, include non-superseded R-only records, admit blank combustor labels, apply 2%, 5% and 10% pairwise thrust tolerances, restrict known final test dates to 2023 onward, vary density and compare monthly with aligned US prices. Broader matching retains the same model label rather than combining model families.

The outputs preserve scenario ranges, record identifiers and changes in pair classifications. Alternative representative-UID selection and a probabilistic or formal rounding-error analysis remain uncompleted; no results are claimed for them. Reconstruction is a deterministic check on published accounting, not a substitute for measurement uncertainty.

The repeated engine–price combinations are calculated scenarios. They do not increase the number of engine observations. Analysis is descriptive, without causal country regressions, time-series inference or significance tests. Original-currency costs and converted costs remain available in the calculation archive.

4. Results

4.1 Sample and matched-record coverage

The eligibility rules retained 504 UIDs representing 397 recorded model labels. Of these, 101 lacked a combustor description. Two BR700-710A1-10 records, 3BR001 and 4BR008, shared basic configuration identifiers but differed in source remarks; both were excluded from primary matching. The remaining 403 records had documented, unambiguous combustor configurations. Seventy-seven records entered 34 strict comparison groups, yielding 52 unique unordered pairs. Twenty-five groups contained two records and nine contained three; 326 otherwise eligible configuration records had no strict comparator.

The primary calculation required identical normalized manufacturer and model labels, exact rated thrust and the same test-engine category, together with different nonblank combustor descriptions. This is narrower than the 2%, 5% and 10% nearby-thrust sensitivities. It is a certification-record comparison and does not establish common-aircraft applicability or a causal combustor effect.

Known final test dates in the eligible sample ranged from 1980 to 2024; 36 dates were missing. Current engine status was missing for 113 records. The known final test dates among strict matched records ranged from 1989 to 2020. Restriction to known final tests from 2023 onward retained 35 candidate records but produced no strict

matched pairs. Accordingly, the March 2026 databank edition supplies an updated compilation, not a sample of newly tested 2026 engines.

4.2 Reconciliation of cycle totals

Reconstruction from the four operating modes identified six UIDs with absolute fuel differences above 2% relative to published totals: 1PW026, 04P20PW196, 04P20PW195, 04P20PW202, 04P20PW204 and 04P20PW203. No eligible record had an absolute NOx reconciliation difference above 2%. Published totals were retained in the base calculation. The differences are audit flags and are not evidence of confirmed manufacturer errors.

Reconstructed totals changed the classification of five of the 52 strict pairs (9.6%). The number showing lower NOx with higher fuel fell from eight to seven. Excluding the six fuel flags left 50 strict pairs and retained all six pairs eligible for the incremental-expenditure calculation.

4.3 Observed fuel-price scenarios

The common price window ran from April 2024 to April 2026 and contained 25 Indian effective dates. Four city quotes per date supplied 100 Indian quote observations. Adding one aligned US Gulf Coast quote per date produced 125 price scenarios. All 25 effective dates had a valid within-month joint US-price and exchange-rate observation; the maximum alignment delay was two calendar days. The daily input window contained 544 weekday dates, 522 observed exchange rates and 519 joint price–exchange-rate observations. No missing value was interpolated.

Table 1. Converted quoted fuel prices at an assumed density of 0.800 kg/litre

Quote basis	Mean USD/kg	Range USD/kg	Mean INR/kg
Chennai	1.4032	1.2613–1.5818	121.38
Delhi	1.3525	1.2169–1.5225	116.99
Kolkata	1.4075	1.2606–1.6564	121.71
Mumbai	1.2649	1.1368–1.4256	109.41
US Gulf	0.7403	0.6198–1.2677	64.22

Each mean uses the 25 aligned effective-date scenarios. Means are arithmetic, not transaction-weighted airline purchase prices.

Mumbai had the lowest mean converted Indian quote at USD 1.2649/kg, followed by Delhi at USD 1.3525/kg. Chennai and Kolkata averaged USD 1.4032/kg and USD 1.4075/kg, respectively. The aligned US quote averaged USD 0.7403/kg. At the common central density, every one of the 100 Indian city-date quotes exceeded its aligned US quote.

These contrasts compare Indian domestic city quotes with a US Gulf Coast wholesale spot series. Conversion to a common currency and mass unit does not harmonize taxes, delivery conditions or contract terms. The differences therefore do not estimate a national airline purchasing-cost premium.

4.4 Fuel–NOx outcomes within strict matched groups

Table 2. Pair classifications using published cycle totals

Lower-NOx record	Pairs	Share of 52 pairs
Lower NOx, lower fuel	26	50.0%

Lower-NOx record	Pairs	Share of 52 pairs
Lower NOx, equal fuel	18	34.6%
Lower NOx, higher fuel	8	15.4%

Lower NOx coincided with lower fuel use in 26 pairs (50.0%) and equal fuel use in 18 pairs (34.6%). Eight pairs (15.4%) showed lower NOx with higher fuel use. Thus, 44 pairs (84.6%) had no additional published fuel requirement for the lower-NOx record. These proportions describe the selected contrasts; shared UIDs and repeated numerical outcomes prevent their interpretation as independent experiments or fleet-wide frequencies.

Forty-two of the 77 strictly matched records were nondominated on published fuel and NOx. A common positive price preserved this set and the fuel-cost ordering in every scenario. The 63,000 engine–price cost combinations (504 × 125) represent repeated accounting scenarios, not additional engine observations.

The incremental-expenditure output applied an analyst-defined denominator screen: the NOx reduction had to be at least the larger of 0.100 kg and 1% of the higher-NOx total. Six of the eight higher-fuel/lower-NOx pairs met this condition, producing 750 pair–price calculations (6 × 125). The screen is neither an uncertainty interval nor a regulatory threshold; all eight pairs remain in the complete pair table.

Table 3. Denominator-eligible fuel–NOx trade-offs

Model	Extra fuel kg	Lower NOx kg	Published ratio	Reconstructed ratio
CF34-10E5A1	3.000	0.114	26.316	22.722
CF34-10E6A1	3.000	0.114	26.316	22.722
CF34-10E7	3.000	0.114	26.316	22.722
PW1133G-JM	0.400	0.128	3.125	0.205
PW1521G	0.200	0.111	1.802	No fuel increase
PW4164	55.000	5.082	10.823	10.660

Ratio unit: kg additional fuel per kg lower NOx. The three CF34 labels repeat the same listed contrast and are not three independent engineering experiments.

4.5 PW4164 expenditure example

For PW4164, UID 1PW049 with a Floatwall combustor reported 906 kg of cycle fuel and 17.232 kg of NOx. UID 7PW081 with Talon II reported 961 kg of fuel and 12.150 kg of NOx. Both records had a rated thrust of 284.68 kN and the same test-engine category. The lower-NOx record therefore required 55 kg more fuel (6.07%) while reporting 5.082 kg less NOx (29.49%). The published accounting slope was 10.823 kg additional fuel per kg lower NOx; reconstruction reduced it to 10.660, a 1.51% change.

Table 4. PW4164 incremental fuel expenditure per kilogram of lower NOx

Quote basis	Mean USD/kg NOx	Minimum	Maximum
Chennai	15.19	13.65	17.12
Delhi	14.64	13.17	16.48

Quote basis	Mean USD/kg NOx	Minimum	Maximum
Kolkata	15.23	13.64	17.93
Mumbai	13.69	12.30	15.43
US Gulf	8.01	6.71	13.72

Each value uses the published 55 kg fuel increment and 5.082 kg NOx reduction. The mean covers 25 dates at 0.800 kg/litre.

On 1 April 2026, additional expenditure was USD 69.72 per engine per reference LTO under the US quote and USD 72.47–81.04 under the Indian city quotes. Corresponding slopes were USD 13.72/kg lower NOx and USD 14.26–15.95/kg, respectively.

The Floatwall record has a final test date of 17 February 1993, whereas the Talon II date is missing. Their listed pressure ratios also differ, at 31.24 and 30.10. The expenditure contrast is therefore hypothetical accounting for two certification records; it is not an observed retrofit abatement cost, an emissions charge or a controlled test of combustor technology.

4.6 Sensitivity results

Table 5. Comparison counts under completed sensitivity specifications

Specification	Pairs	Higher fuel / lower NOx	Ratio eligible
Primary exact model, thrust and test category	52	8	6
Reconstructed fuel and NOx	52	7	5
Exclude six fuel reconciliation flags	50	8	6
Final test date 2023 onward	0	0	0
Same model, thrust within 2%	84	22	20
Same model, thrust within 5%	84	22	20
Same model, thrust within 10%	86	22	20
Include non-superseded R-only	56	8	6
Include blank combustor labels	62	13	10

Nearby-thrust comparisons retain identical normalized model labels and test-engine categories, with relative thrust distance divided by the smaller rating. They are not family-reference-rating matches.

Reconstruction was especially influential for small reported fuel differences. For PW1133G-JM, the reported 0.400 kg fuel increment became approximately 0.0263 kg, reducing its fuel–NOx slope from 3.125 to 0.205. For PW1521G, the reported 0.200 kg increment disappeared because both reconstructed fuel totals were 265.140 kg. Consequently, the number of denominator-eligible positive trade-offs fell from six to five.

Thrust tolerances of 2% and 5% each produced 84 pairs; a 10% tolerance produced 86. All three specifications contained 22 higher-fuel/lower-NOx pairs and 20 eligible ratios. Including non-superseded R-only records produced 56 pairs, with eight positive trade-offs and six eligible ratios. Allowing a blank combustor description

to contrast with a documented description produced 62 pairs, including 13 positive trade-offs and ten eligible ratios. These broader samples are separate sensitivity specifications, not additional observations for the strict base sample.

Using densities of 0.775 and 0.840 kg/litre changed scenario expenditures by +3.23% and −4.76%, respectively, relative to 0.800 kg/litre. When country densities varied independently, the April 2026 Mumbai quote difference changed from +3.93% at the central densities to −4.11% with India at 0.840 and the US at 0.775 kg/litre. This was the only one of the 100 central-density city-date orderings that could reverse within those bounds.

The largest absolute monthly-versus-aligned US price difference occurred in March 2026. The monthly arithmetic mean was USD 1.2209/kg, compared with USD 0.9041/kg for the aligned observation, an increase of 35.04%. Monthly INR values were formed by converting daily US observations with same-day exchange rates before averaging.

Only the PW4164 pair remained eligible when the denominator screen required a 5% NOx reduction, or when a separate screen required at least a 1% fuel increase. These are descriptive selection sensitivities, not significance tests. No numerical findings are claimed here for alternative representative-UID selection or a formally specified rounding-error model, because those checks are not documented in the completed outputs.

4.7 Reporting boundary

The results quantify quoted-price valuation of selected certification-record contrasts. They neither estimate country fleet emissions nor validate operational engine substitutions. Exact-value classifications and reconstruction sensitivities are reported; formal rounding-sensitive membership and representative-UID sensitivities are not claimed.

5. Discussion

5.1 Meaning of the observed fuel–NOx relationship

The strict comparisons contain more lower-NOx records with lower or equal fuel use than with higher fuel use. That pattern rules out a universal positive fuel penalty within the selected records. It does not identify a technological law: exact model and thrust matching leaves pressure ratio, test conditions and other configuration differences uncontrolled.

The architecture-dependent relationship described by Kyprianidis and Dahlquist [2] provides a plausible context for these mixed outcomes. Improving propulsive efficiency, changing thermal efficiency and modifying combustion need not have the same NOx response. The present records describe existing configurations over a fixed LTO cycle; they do not optimise otherwise identical engines over a flight mission.

Li et al. [10] reported higher operational NO emission factors for some newer engine generations. This does not contradict the present pair classifications. Their outcome is nitric oxide per kilogram of fuel under observed operating phases, whereas ours is total NOx mass over fixed mode durations. Differences in species, normalisation and engine selection prevent a direct numerical comparison.

5.2 Price scenarios value record differences without changing dominance

A common positive price preserves fuel ranking and dominance. Price scenarios consequently value an existing contrast without generating a different physical frontier. This invariance is an algebraic property of the expenditure equation, rather than evidence that market conditions cannot influence future engine design or airline behaviour.

PW4164 illustrates a persistent positive accounting slope, while the small-increment pairs show why persistence must be checked. Even for PW4164, the expenditure covers fuel only. Miller et al. [5] included fuel-production and environmental costs in assessing NOx regulation. An operator’s investment decision would also require acquisition, installation, maintenance and mission-performance information.

The higher Indian quoted expenditures arise from the selected commercial price bases. Domestic city quotes and US wholesale spot prices differ in taxes, delivery and contracting. Unit conversion removes currency and volume differences but does not harmonise those market terms. The calculation is transferable to financial planning only after substituting the operator's delivered price.

5.3 Reconstruction exposes the fragility of small positive penalties

The expenditure ratio divides a difference between fuel totals by a difference between NOx totals. Near-zero differences can therefore be sensitive even when each total reconciles closely. The much smaller reconstructed PW1133G-JM increment and the disappearance of the PW1521G increment demonstrate this problem. Neither a positive published numerator nor its displayed decimal precision establishes a repeatable operational penalty.

Reconciliation locates accounting discrepancies rather than proving source errors. The denominator screen limits ratios based on small NOx differences, but it cannot supply measurement confidence. Stettler et al. [24] incorporated measurement and operational uncertainty in an airport inventory. Comparable uncertainty inputs would be needed here before deterministic scenario ranges could be interpreted probabilistically.

5.4 Certification evidence and operational applicability

PW4164 is comparatively stable under reconstruction, yet its historical and incomplete test metadata limit application. Different reported pressure ratios also prevent attribution of the observed contrast to combustor technology alone. Independent aircraft applicability and comparable operational evidence are necessary before treating the two records as alternatives available to an operator.

Harlass et al. [9] found that using ground measurements from the operating engine improved agreement with measured flight NOx relative to reliance on certification inputs. For the present study, this supports validation using the same applicable aircraft–engine configuration. Their reported performance cannot supply an uncertainty bound for unrelated databank UIDs.

The absence of strict pairs in the recent-test sensitivity means the analysis does not establish the same comparison pattern for newly tested engines. A 2026 source edition updates the compilation, not every underlying test. Likewise, the price window ending in April 2026 does not support a full-year 2026 expenditure estimate.

5.5 Sensitivity to sample definition, density and observation timing

Broader thrust tolerances increased both comparison coverage and the number of higher-fuel/lower-NOx contrasts. Sample definition therefore affects the descriptive mix of outcomes. Thrust proximity does not resolve compatibility or confounding, so these specifications remain separate sensitivities. The R-only sensitivity also shows why exclusion of revised-only records should be described as a design choice rather than a judgement that revised data are invalid.

Density and timing affect prices through different mechanisms. Density changes expenditure through mass conversion, and separate country assumptions can reverse a close ordering. Observation timing changes the quote itself: the March 2026 monthly US mean differed materially from the aligned observation. Valuation at an Indian effective date and valuation across available monthly US quotes are distinct specifications, neither representing transaction-weighted purchases.

5.6 Environmental interpretation and contribution

Environmental interpretation requires another modelling step. Prather et al. [17] evaluated uncertain climate responses to CO2 and non-CO2 mitigation. The present expenditure slope measures no such response. Mission emissions and a stated climate metric would be needed for climate valuation; atmospheric concentrations and exposure would be needed for health valuation.

The accounting exercise identifies contrasts worth further examination and makes their sensitivity visible. An extension for India or another country should first verify common aircraft applicability, then link records to

observed operations and delivered prices. Those additions would permit evaluation of a practical option rather than merely valuation of a certification contrast.

6. Conclusion and limitations

6.1 Conclusion

Among 52 strict certification-record pairs, 44 combined lower reported NOx with lower or equal reported fuel use. A general fuel penalty for lower LTO NOx is therefore unsupported within this sample. Reconstruction changed five pair classifications, showing why published differences and calculated differences must remain separate.

Prices changed expenditure without changing physical dominance. The historical PW4164 contrast retained a positive fuel increment under reconstruction; its mean published incremental expenditure was USD 8.01 per kilogram of lower NOx under the US quote and USD 13.69–15.23 under the Indian city quotes. These conditional values are useful for screening records, but cannot serve as retrofit costs or harmonised national procurement comparisons.

The study provides a reproducible link between reference-cycle propulsion data and quoted-price sensitivity. Practical engine or policy decisions require the additional operational, compatibility and environmental evidence identified below.

6.2 Limitations

The engine evidence is historical and incomplete in specific fields. Known final test dates span 1980–2024; 36 dates and 113 current engine-status values are missing. Known dates among strict matched records end in 2020. Restriction to final tests from 2023 onward retained 35 candidate records but no strict matched pairs. The March 2026 databank edition therefore cannot be interpreted as evidence from engines tested in 2026 or as a representative sample of current fleet operations.

Comparability is limited by record selection and configuration information. Of the 403 records eligible for primary configuration matching, only 77 had a strict comparator. Exact model, thrust and test-category matches do not control pressure ratio, test history or other engine differences, and common aircraft applicability has not been independently verified. The wider thrust tolerances alter the comparison set without resolving these differences. The 52 pairs share UIDs, and three CF34 model labels repeat the same numerical contrast; pair percentages are descriptive and cannot be treated as independent experimental outcomes or fleet-wide frequencies.

The reference LTO cycle uses fixed mode durations and certification fuel flows. It does not reproduce actual taxi time, derated takeoff, airport conditions, maintenance state or a complete flight. Cruise emissions and mission fuel use are outside the calculation. Lower reference-cycle NOx mass therefore does not establish the size of a local exposure reduction, health benefit or net climate benefit.

The price scenarios also have restricted commercial and temporal coverage. Four Indian domestic city quote series are compared with a US Gulf Coast wholesale spot series. Currency and volume conversion do not harmonize taxes, delivery charges, contract terms or airline procurement practices. The common window ends in April 2026, and its 25 date-aligned observations per price basis are not full-year 2026 or transaction-weighted prices. Monthly versus aligned US quotes can yield materially different expenditures, so the chosen time basis must remain explicit.

Fuel densities of 0.800, 0.775 and 0.840 kg/litre are planning and sensitivity assumptions rather than measured delivery densities. Independent country-density variation can reverse a close price ordering. The resulting ranges are conditional scenarios, not confidence intervals. Similarly, the 2% reconciliation flags and the ratio screen requiring at least 0.100 kg and 1% lower NOx do not quantify measurement uncertainty or prove source errors. Sensitivity checks for alternative representative-UID selection and a formally specified rounding-error model are not documented in the completed outputs.

Finally, the incremental-expenditure slope includes additional fuel expenditure only. It excludes acquisition, installation, maintenance and implementation costs, as well as environmental damages. Repeated engine–price combinations do not add independent engine evidence. The analysis cannot identify a causal combustor effect, estimate a retrofit abatement cost or justify an emissions charge. Further work should validate selected contrasts for a common applicable aircraft–engine configuration and observed operations, using delivered fuel prices and documented measurement uncertainty.

Data availability

The source databank and quoted-price series are publicly obtainable from the organisations cited in Methods. The calculation archive contains the extracted source workbook, dated exchange-rate inputs, UID-level reconstruction, pair definitions, price alignment, scenario tables and analysis script. The window is explicitly limited to April 2024–April 2026. No public repository DOI or unrestricted redistribution licence is claimed for the assembled archive.

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