

Article

Environmental and Cost Analysis of Supersonic Cargo Transport: A Comparative Study with Subsonic Aircraft and Other Freight Modes

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Abstract

Rapid-delivery logistics is reviving interest in supersonic cargo aircraft, yet their environmental and economic viability against subsonic and surface freight remains uncertain. This screening-level assessment combines a fuel-based emissions model, a Breguet supersonic performance grid, and a direct operating cost (DOC) decomposition with Monte Carlo uncertainty propagation, for a 1-ton payload over 500, 1500, and 5000 km. Relative to the 1500 km subsonic benchmark, a conservative first-generation supersonic case yields $2.30\times$ the CO₂ intensity and $2.21\times$ the DOC, while the Monte Carlo median is $1.50\times$ the subsonic CO₂ intensity (0.82 kg/ton-km). Across the deterministic parameter grid the CO₂ intensity spans 0.52–1.44 kg/ton-km ($0.96\text{--}2.64\times$ subsonic), with a narrower Monte Carlo 90% interval of 0.67–1.02 kg/ton-km ($1.23\text{--}1.87\times$). The DOC is about \$2.08/ton-km for a fully filled 1-ton functional unit—upper-leaning, as whole-aircraft crew and fees and the small-payload capital and maintenance rates fall on the costed ton; once load factor (0.5–0.85; filled fraction, not capacity utilization) and fuel-price variability are propagated, the Monte Carlo cost per delivered ton-km spans \$2.5–3.5/ton-km (90% interval). Supersonic cargo thus remains a niche, high-value-of-time option: substantial propulsion and aerodynamic gains, with climate accounting expanded to effective radiative forcing (ERF/CO₂e), are needed before competitive, sustainable deployment becomes plausible.

Keywords: supersonic transport; cargo logistics; emissions analysis; operational costs; sustainability; freight transport; environmental impact

1. Introduction

The global logistics industry faces increasing pressure to deliver goods faster to meet the demands of modern supply chains [1]. Traditional subsonic cargo aircraft, while reliable, are limited in speed, which creates bottlenecks for time-sensitive shipments. Supersonic aircraft, capable of exceeding Mach 1, present a potential solution to reduce delivery times significantly. However, their adoption for cargo transport requires a thorough evaluation of environmental impact and economic viability compared to existing options such as subsonic aircraft, shipping, and rail: the environmental baseline of the incumbent modes is well documented, from economy-wide freight carbon intensities [2] to ship-level emission inventories [3], while the economic value of transit-time savings is quantified in the trade literature [4].

Recent work on supersonic aviation has concentrated on passenger concepts, with emphasis on low-boom signatures [5,6], market-demand analyses [7], propulsion cycles [8],



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and NO_x emissions and their ozone/climate impacts [9–11]. Cargo-specific studies remain scarce, leaving open questions about payload fractions, stage-length economics, and non-CO₂ climate forcing [12,13]. Standard freight assessments address surface modes such as trucking, rail, and maritime shipping [14–16]—with recent work extending to operational emission reduction in shipping, such as speed and voyage optimization for compliance with the International Maritime Organization’s Carbon Intensity Indicator (CII) [17]—but do not capture supersonic performance sensitivities (Mach number, lift-to-drag ratio, specific fuel consumption) or uncertainty in emission indices [18]. To our knowledge, no physics-grounded comparison simultaneously spans supersonic, subsonic, and surface freight with uncertainty propagation and a transparent DOC decomposition.

We define “screening-level” as deliberately simplified in three respects: (i) mission performance via Breguet rather than full trajectory optimization, (ii) stylized DOC inputs rather than operator-specific ledgers, and (iii) reporting mass emissions without effective radiative forcing (ERF/CO₂e). Section 2 lists the simplifying assumptions that bound applicability.

This paper makes four contributions: (1) a fuel-based emissions model with mission overheads and Monte Carlo uncertainty propagation for supersonic and incumbent modes; (2) a reproducible supersonic performance grid and scenario labels that connect Mach/L/D/SFC to block fuel; (3) a DOC decomposition with sensitivity to capital/maintenance assumptions and fuel price/load factor; and (4) a cross-modal comparison over common functional units (1 ton over 500, 1500, and 5000 km). The functional unit isolates modal performance while remaining easy to scale. Section 2.1 shows that volumetric constraints cap early supersonic payloads at 5–10 tons, and that the modal ranking is invariant to payload scaling.

We frame this work as a screening-level techno-environmental and cost assessment guided by two research questions. **RQ1:** For a 1-ton functional payload under the screening assumptions of Section 2 (Mach 1.6–2.2, L/D 6.0–8.0, SFC 20–35 mg/(N·s)), what CO₂ intensity range (parameter grid plus Monte Carlo uncertainty) arises for first-generation supersonic cargo relative to advanced subsonic air freight and surface modes at the 1500 km baseline, and how do the deterministic stage-length sensitivities at 500 and 5000 km reshape that comparison? What direct operating cost (DOC) intensity range arises at the 1500 km baseline, and how do fixed mission overheads drive the CO₂ stage-length scaling? **RQ2:** What break-even value of time (VOT) does the supersonic DOC premium imply, and how does that break-even compare with plausible willingness-to-pay ranges for time-critical freight? Previewing the answer, the 1500 km baseline yields CO₂ and DOC penalties of 2.30× and 2.21×, with sensitivity bounds that do not overturn this qualitative conclusion.

2. Materials and Methods

Methods roadmap. The analysis flowed through five linked stages, and the headline emissions and cost results traced back along this pipeline (the illustrative value-of-time and carbon-price comparisons additionally drew on external valuation ranges): (1) a *mission definition* fixed the functional unit (1 ton over 500/1500/5000 km); (2) an *emissions model* converted block fuel to CO₂, NO_x, and H₂O intensities; (3) a *Breguet supersonic performance grid* mapped Mach/L/D/SFC to block fuel and fed the emissions model; (4) a *direct operating cost (DOC) decomposition* converted block fuel and time into \$/ton-km; and (5) a *Monte Carlo layer* propagated parameter uncertainty through stages (2)–(4) to produce percentile bands and a break-even VOT. Sections 2.4 and 2.5 define stages (3)–(4); the surface modes entered stages (2) and (4) through published intensity factors. Three distinct analysis tracks ran through this pipeline, and we kept them separate throughout:

- (i) the *baseline comparison* was deterministic and fixed at 1500 km, with the Breguet grid—solved at that stage length—supplying the supersonic cruise emission factor;

- (ii) the *stage-length sensitivity* was also deterministic, re-evaluating the fixed-overhead-plus-constant-cruise intensity model of Section 2.3 at 500–5000 km without re-solving the Breguet equation (the full Breguet weight build-up was re-solved across distance only for the weight-limited-range and value-of-time analysis presented in the Discussion);
- (iii) the *uncertainty analysis* (Section 2.6) held the stage length at 1500 km and propagated parameter uncertainty by Monte Carlo.

Wherever a Monte Carlo interval is quoted in Sections 2.3 or 2.4, it is a forward reference to track (iii), not part of the deterministic model definitions.

What “screening-level” means (and does not).

The three simplifications introduced in the Introduction (Breguet mission performance, stylized DOC inputs, and mass-emissions-only climate metrics) are each revisited in Section 2.7. The consequence is that the results are intended to *rank concepts and bound penalties*, not to size fleets or certify designs. Equivalently, the analysis evaluated a technically feasible first-generation aircraft on a stylized mission, not a commercially realistic transportation system with networks, schedules, and demand; the limitations subsection states the likely direction of bias for each simplification.

2.1. Mission Definition

The functional unit was the transport of 1 ton of cargo over stage lengths of 500, 1500, and 5000 km. These distances bracketed regional, medium-haul, and intercontinental missions and captured the strong stage-length dependence of aircraft block fuel and economics. Payload was held constant across modes to isolate modal performance. Scaling the payload up to plausible early supersonic capacities (5–10 tons) did not change the *relative* ranking of modes: the distance-proportional cruise terms were payload-linear, while the fixed mission overheads and per-mission fees were spread over more tons, lowering their per-ton contribution. A larger payload would therefore, if anything, narrow the supersonic penalty, making the 1-ton normalization conservative. Early supersonic cargo concepts are nonetheless volume-limited by slim fuselages: a representative low-boom cross-section of ~ 3 m *peak* diameter with a 20 m bay encloses a geometric internal volume of ~ 140 m³ (evaluated at the peak cross-section over the full bay length, so the packable-volume discount below already absorbs fore/aft taper), but fuselage taper, the poor fit of rectangular unit-load devices to a slim circular cross-section, and access clearances reduce the packable volume to roughly 40–50% of this (~ 55 – 70 m³). At belly-cargo packing densities of 100–150 kg/m³ (narrow-body analogues), this gives 5–10-ton practical payloads, a geometric estimate representative of first-generation low-boom cargo concepts. Subsonic and supersonic aircraft intensities were derived from representative freighter concepts (e.g., B777F-class subsonic at ~ 90 – 100 -ton design payload and first-generation low-boom cargo concepts) and normalized to the 1-ton functional unit, while shipping (container feeder) and rail (diesel freight) intensities were drawn from regulatory inventories [19,20]. The subsonic emission factor (0.545 kg/ton-km) reflected a modern widebody freighter baseline rather than a fleet average; the Breguet setup reproduced this benchmark. Stage-length sensitivity for aviation was modeled by combining a distance-proportional cruise term with a fixed 120 kg CO₂ overhead for subsonic and 350 kg CO₂ for supersonic operations (taxi, take-off, climb, descent, and diversion reserves); these overhead values are modeling assumptions calibrated to the short-mission fuel-burn behavior in the ICAO methodology [21], not figures reported by ICAO. The fixed overhead was anchored to short-block operations; for long-haul missions it slightly understated total reserves because the overhead did not escalate with distance, although the cruise-fuel contingency embedded in the Breguet fuel fraction did scale with mission fuel. Surface modes were treated as linear with distance due to negligible fixed fuel. Throughout the paper, “load factor” denotes the cost-spreading divisor introduced in

the abstract—the fraction of the costed 1-ton functional unit’s capacity actually filled—not aircraft payload-capacity utilization. Baseline intensity and cost calculations therefore corresponded to the 1-ton costed unit fully filled (load factor 1.0); the Monte Carlo analysis separately sampled values of 0.5–0.85, which raised the per-carried-ton DOC.

2.2. Notation and Units

Throughout, “ton” denotes a metric tonne (1000 kg). Emission intensities use kg/ton-km, cost intensities use \$/ton-km, and SFC is reported in mg/(N·s) (thrust-specific fuel consumption). CO₂ refers to mass emissions throughout the headline results; CO₂e enters the quantitative results only once—as an explicitly illustrative ERF-based estimate in the Discussion (Section 4)—while elsewhere it is referenced only to delimit scope, so it is not part of the quantitative comparison. Two capacity-related terms recur in fixed, distinct senses. “Load factor” is a *cost-spreading divisor*: the filled fraction of the costed 1-ton functional unit, by which the DOC was divided to obtain cost per *delivered* ton-km (baseline 1.0; Monte Carlo range 0.5–0.85, Table 1); it is *not* aircraft payload-capacity utilization. “Utilization”, by contrast, denotes annual flying time (block-h/year), and it entered only the capital-recovery calculation (Section 2.5).

2.3. Emissions Modeling

The CO₂ emissions per mission were modeled as the sum of a fixed mission overhead and a distance-dependent cruise term and were then normalized to an intensity:

$$m_{\text{CO}_2} = m_{\text{fixed}} + (EF_{\text{cruise}} \times m_{\text{payload}} \times d), \quad (1)$$

$$I_{\text{CO}_2} = \frac{m_{\text{CO}_2}}{m_{\text{payload}} d} = \frac{m_{\text{fixed}}}{m_{\text{payload}} d} + EF_{\text{cruise}}, \quad (2)$$

where m_{CO_2} is mission CO₂ mass (kg), m_{fixed} is the fixed mission overhead (kg CO₂; 350 kg supersonic, 120 kg subsonic), m_{payload} is payload mass (metric tons), d is stage length (km), and EF_{cruise} is the cruise emission factor in kg/ton-km (1.02 supersonic, 0.465 subsonic, evaluated at, and held constant from, the 1500 km baseline). These cruise factors are quoted to three significant figures; the stage-length table reported in Section 3.1 was computed from the unrounded values (≈ 1.021 supersonic, ≈ 0.4653 subsonic), which the rounded constants reproduced to within a few kilograms at all stage lengths. *Dimensional check*: m_{fixed} (kg) divided by m_{payload} (ton) and d (km) gives kg/ton-km, the same units as EF_{cruise} , so I_{CO_2} is in kg/ton-km. The intensity form made the stage-length dependence explicit: the fixed-overhead contribution decayed as $1/d$ while the cruise term was constant, so short missions were penalized most. *Scope of the two aviation models*. Equation (1) and the Breguet model of Section 2.4 are two stages of a single framework rather than competing formulations: the Breguet grid generated the supersonic cruise emission factor at the 1500 km baseline, and Equation (1) extrapolated that Breguet-calibrated factor across stage lengths, treating EF_{cruise} as a stage-length-independent technology descriptor—equivalent to assuming an aircraft sized for each mission rather than one fixed airframe stretched across all distances. All the cross-modal stage-length results used this single overhead-plus-cruise framework; the full Breguet weight equation was re-solved as a function of distance only in the value-of-time analysis, where the weight-limited maximum range of a fixed configuration was the quantity of interest. The two treatments coincided at the 1500 km calibration point by construction and are reconciled quantitatively in Section 3.1. Evaluated at 1500 km these combined to block emission factors ($EF_{\text{block}} \equiv I_{\text{CO}_2}$) of 1.25 kg/ton-km (supersonic) and 0.545 kg/ton-km (subsonic). The subsonic EF_{block} reflected a widebody freighter benchmark; all baseline EFs and DOCs corresponded to the 1-ton costed unit

fully filled (i.e., load factor 1.0 in the cost-spreading sense defined in Section 2.1), not to aircraft payload-capacity utilization. Trucking, shipping, and rail were modeled linearly with emission factors of 0.080, 0.010, and 0.0265 kg/ton-km, respectively [14,19,20]; the rail value was the Office of Rail and Road's reported 2020–21 freight intensity (26.5 g CO₂e per net tonne-kilometre, a blended diesel-and-electric traction average), and the shipping value was a representative container-ship CO₂ intensity consistent with the ship-type carbon-intensity estimates of the Fourth IMO GHG Study 2020 (its Section 3.3.1 and Tables 59–61 give carbon intensity per ship type and size category, with the corresponding figures in its Annex F). The supersonic parameters were derived from the analysis in Section 2.4. Fuel burn was inferred from CO₂ via a combustion factor of 3.16 kg CO₂ per kg fuel; because kerosene, diesel, and heavy fuel oil share a carbon mass fraction of ~85–86%, the same factor applied across the aviation and surface liquid-fuel modes to within a few percent:

$$m_{\text{fuel}} = \frac{m_{\text{CO}_2}}{3.16} \quad (3)$$

NO_x followed mode-specific emission indices (EI, g/kg fuel):

$$m_{\text{NO}_x} = EI_{\text{NO}_x} \times \frac{m_{\text{fuel}}}{1000}, \quad (4)$$

using mid-range values of 15, 20, 15, 70, and 40 g/kg for subsonic, supersonic, trucking, shipping, and rail, respectively; the aviation indices followed [18] and the surface-mode NO_x indices were taken from the EMEP/EEA Air Pollutant Emission Inventory Guidebook [22] (road transport, 1.A.3.b; navigation, 1.A.3.d; railways, 1.A.3.c). The adopted mid-range values lay within the guidebook's fuel-based ranges (marine ~69–72, rail ~40–63, and road 10–47 g/kg), with the 15 g/kg trucking figure representing a modern Euro V/VI heavy-duty engine at the low end of the road-fleet range. The adopted 70 g/kg shipping value was the deterministic point estimate, within the marine HFO/MDO range, while the Monte Carlo layer sampled a wider 50–100 g/kg band (Table 1) spanning fuel-quality and engine variability. The supersonic EI bounds (15–25 g/kg) reflected conceptual supersonic transport (SST) combustor projections and scaled high overall-pressure-ratio (OPR) subsonic engines [18], while the subsonic bounds (8–20 g/kg) bracketed current ICAO fleet-average scatter [18]; the qualitative trade-off whereby higher combustor temperatures raise NO_x is documented by Miake-Lye and Hauglustaine [23]. These EIs were held constant with operating condition, a simplification because NO_x formation varies with combustor temperature, pressure, altitude, and throttle setting; altitude/OPR-resolved data for conceptual engines were unavailable, so reported uncertainty likely understated tail risk if higher SFC correlated with higher EI. Water vapor scaled stoichiometrically with fuel burn, with an emission index of 1.23 kg H₂O per kg fuel for kerosene-class fuels:

$$m_{\text{H}_2\text{O}} = 1.23 \times m_{\text{fuel}}. \quad (5)$$

The NO_x ranges reported in the Results section spanned the full literature EI bounds for each mode (e.g., 15–25 g/kg supersonic) applied to the baseline fuel burn, rather than Monte Carlo percentiles; although the Monte Carlo layer did sample the EI distributions (Table 1), the NO_x column reports the full literature bounds for transparency, while the 90% Monte Carlo interval is reported separately for the CO₂ and DOC intensities. The stage-length results converted fixed CO₂ overheads to fuel via Equation (3) before applying Equations (4) and (5). We assumed complete combustion when inferring fuel from CO₂; the 3.16 factor reflected the shared ~85–86% carbon content of Jet-A, diesel, and heavy fuel oil, while alternative fuels (e.g., SAF with different stoichiometry or EI) were outside

scope [24,25]. Monte Carlo sampling kept NO_x EI independent of SFC; if less efficient engines also exhibit higher EI, true uncertainty may be larger.

Overhead mapping and benchmarking. The fixed CO₂ overheads (350 kg supersonic, 120 kg subsonic) were derived from ICAO block-fuel fractions for short missions [21], assuming taxi, take-off, climb, descent, and diversion reserves constituted roughly 15–20% of total mission CO₂ for the 1500 km baseline (about 19% for the supersonic case, 350/1881 kg CO₂, and about 15% for subsonic, 120/818 kg), and they were obtained from that overhead fuel using the 3.16 kg CO₂/kg combustion factor (the inverse of Equation (3), which is written in the CO₂-to-fuel direction). Varying these overheads from −25% to +50% shifted the 500 km intensities by about −0.17 to +0.35 kg/ton-km for the supersonic case and by about −0.06 to +0.12 kg/ton-km for the subsonic case, and the 1000 km intensities by exactly half those amounts because the overhead contribution scaled as $1/d$ —the subsonic shifts were smaller because the absolute overhead was smaller (120 versus 350 kg CO₂), and cruise dominated the 500 km block fuel even at short range; the long-haul results changed marginally for both modes because cruise dominated further as distance grew. For external benchmarking, the subsonic stage-length outputs (0.71 kg/ton-km at 500 km; 0.49 kg/ton-km at 5000 km) sat within roughly 10–15% of ICAO Carbon Calculator/B777F-class block-fuel intensities (0.65–0.75 and 0.45–0.50 kg/ton-km, respectively), indicating that the simple overhead-plus-cruise structure preserves realistic short-/long-haul behavior. To broaden this benchmark beyond a single aircraft class, the implied fixed overhead was cross-checked against per-type block-fuel-versus-distance data from the aviation master emissions calculator annex of the EMEP/EEA air pollutant emission inventory guidebook [22], whose input values are reproduced in Table A1 of Appendix A: regressing each type's tabulated block fuel (ICAO landing–take-off cycle plus climb/cruise/descent fuel) on great-circle stage length over 232–1389 km ($R^2 > 0.999$) yielded implied fixed (non-cruise) fuel burns of 3782, 2311, and 5015 kg for the B777F-, B767-300F-, and B747-400F-class types, respectively, which, converted at 3.16 kg CO₂/kg fuel and normalized by each freighter variant's published design payload (107, 57, and 113 t), implied fixed overheads of approximately 112–140 kg CO₂ per design-payload ton. Because the underlying per-type fuel data were fleet-average values for the corresponding passenger variants, these implied overheads are indicative rather than exact; the 120 kg subsonic assumption fell within this bracket, toward its lower edge, and, if anything, understated the overhead implied for the smaller B767-class and older B747-class freighters (128–140 kg), which would modestly overstate the short-stage supersonic-to-subsonic ratio, while the +50% overhead case (180 kg) bounded even the largest implied value. No operational supersonic freighter exists against which the 350 kg value could be benchmarked directly; it was therefore carried strictly as a first-generation modeling assumption whose influence on the results was bounded by the same −25%/+50% sensitivity.

2.4. Supersonic Performance Grid

A physics-based supersonic model replaced ad hoc emission factors. This subsection defines the deterministic Breguet grid only—solved at the 1500 km baseline stage length—whose role within the single framework of Section 2.3 was to generate the supersonic cruise emission factor and scenario envelope that fed Equation (1); re-solved as a function of stage length, the same model also located each configuration's weight-limited maximum range for the value-of-time analysis, while stage-length sensitivity and Monte Carlo propagation were separate analysis tracks (see the roadmap at the start of Sections 2 and 2.6). We implemented the Breguet range equation in its thrust-specific fuel-fraction form [26],

$$\frac{m_{\text{fuel}}}{m_{\text{gross}}} = 1 - \exp\left(-\frac{(1000 R) \cdot \text{SFC} \cdot g}{(L/D) \cdot V}\right), \quad (6)$$

where R is stage length in km (the factor 10^3 converts to meters), SFC is thrust-specific fuel consumption in kg/(N·s), V is cruise speed in m/s, $g = 9.81 \text{ m/s}^2$, and L/D is dimensionless. Because SFC is mass-thrust-specific (kg per N·s), g appears in the numerator so that the exponent is dimensionless: with R in m, SFC in $\text{kg N}^{-1}\text{s}^{-1}$, g in m s^{-2} , L/D dimensionless, and V in m s^{-1} , substituting $1 \text{ N} = 1 \text{ kg m s}^{-2}$ reduces $R \cdot \text{SFC} \cdot g / [(L/D) V]$ to a pure number. We solved for gross take-off weight by iterating fuel fractions until payload + fuel + OEW (with OEW/MTOW = 0.52) converged. The 5% mission reserve and the 0.52 operating-empty-weight fraction were modeling assumptions representative of first-generation low-boom concepts, while the Mach band and cruise-altitude envelope (50,000 ft) followed [9]. The 5% reserve was a cruise-fuel contingency carried inside the Breguet fuel fraction, whereas the taxi, take-off, climb, descent, and diversion reserves entered only through the fixed mission overhead; the two reserve terms were therefore additive and not double-counted. We evaluated scenarios spanning Mach 1.6–2.2, lift-to-drag ratio (L/D) 6.0–8.0, and cruise specific fuel consumption (SFC) 20–35 mg/(N·s). These ranges were anchored to published conceptual designs rather than chosen ad hoc: the Mach band bracketed NASA/ICAO low-boom conceptual cruise studies [9], while the X-59 low-boom demonstrator itself flew just below this band at Mach 1.4 [6]; the L/D band centered on cruise-average values (≈ 7) reported for low-boom supersonic business-jet (SBJ) concepts [5], with 6.0 a pessimistic cargo-volume allowance and 8.0 an advanced-aerodynamics target; and the SFC band followed variable-cycle engine study values and their higher-Mach off-design sensitivity [8]. Across the grid, cruise-phase CO_2 intensities spanned 0.29–1.20 kg/ton-km and block intensities (cruise plus the fixed mission overhead of taxi, take-off, climb, descent, and diversion reserves) spanned 0.52–1.44 kg/ton-km. Because all the grid points were evaluated at the 1500 km baseline, the fixed overhead added a constant $\approx 0.23 \text{ kg/ton-km}$, so each block intensity was its cruise intensity plus that increment (e.g., the 0.61 kg/ton-km baseline cruise became ~ 0.85 block). Sensitivity analysis (one-at-a-time) highlighted SFC as the dominant driver ($\pm 40\%$), with L/D ($\pm 20\%$) and Mach ($\pm 15\%$) secondary. The conservative cargo value (1.25 kg/ton-km) corresponded to $M = 1.8$, $L/D = 6.0$, $\text{SFC} = 35 \text{ mg/(N·s)}$ plus overhead; the $L/D = 6.0$ choice was a pessimistic allowance for cargo volume penalties relative to Concorde-era values (about 7–7.5). Full scenario outputs are reproducible with the accompanying code repository (see Data Availability).

To aid replication, SFC in mg/(N·s) was converted as $\text{SFC}_{\text{SI}} = \text{SFC} \times 10^{-6} \text{ kg/(N·s)}$, which slotted directly into the Breguet exponent $(1000 R) \cdot \text{SFC}_{\text{SI}} \cdot g / [(L/D) \cdot V]$ (matching Equation (6), with g in the numerator). A worked numeric check confirmed the regime. For the baseline configuration ($M = 1.8$, $V \approx 531 \text{ m/s}$ at 50,000 ft, $L/D = 7.0$, $\text{SFC} = 27.5 \text{ mg/(N·s)}$, $R = 1500 \text{ km}$) the exponent was

$$\frac{(1000 R) \cdot \text{SFC} \cdot g}{(L/D) \cdot V} \approx \frac{(1.5 \times 10^6)(27.5 \times 10^{-6})(9.81)}{7 \times 531} \approx 0.11, \quad (7)$$

an $\mathcal{O}(10^{-1})$ quantity that gave a closed-form cruise fuel fraction of ~ 0.10 . After the iterative gross-weight build-up (which raised the required fuel as MTOW grew) and the fixed mission overhead (120 kg CO_2 subsonic, 350 kg CO_2 supersonic), the resulting block CO_2 intensity was of order 1 kg/ton-km ($\sim 0.85 \text{ kg/ton-km}$ after overhead), consistent with the baseline configuration of the parametric grid (0.61 kg/ton-km cruise plus the $\approx 0.23 \text{ kg/ton-km}$ overhead). This dimensional and order-of-magnitude check confirmed

the numerator placement of g : it yielded a $\mathcal{O}(10^{-1})$ exponent, whereas a denominator placement would mis-scale the fuel burn by about three orders of magnitude.

We used consistent scenario labels: *baseline aero* ($M = 1.8$, $L/D = 7.0$, $SFC = 27.5$ mg/(N·s); 0.61 kg/ton-km cruise, ~ 0.85 with overhead), *conservative cargo* ($M = 1.8$, $L/D = 6.0$, $SFC = 35$ mg/(N·s); 1.25 kg/ton-km block), and *optimistic* ($M = 1.8$, $L/D = 8.0$, $SFC = 20$ mg/(N·s); 0.59 kg/ton-km block). Here “baseline aero” denotes this aerodynamic configuration only; it is distinct from the 1500 km baseline *mission* and from the subsonic *benchmark*, and the headline case is the *conservative cargo* scenario rather than the baseline aero. The three named scenarios held Mach at 1.8 to isolate the L/D – SFC effect, whereas the *scenario envelope* denoted the min/max over the full grid, including Mach 1.6–2.2 (0.52–1.44 kg/ton-km block). The Monte Carlo aerodynamic draws (defined in Section 2.6) were centered on the baseline-aero configuration, but the results were interpreted relative to the conservative 1.25 kg/ton-km point, which sat above the median of the simulated distribution. The scenario envelope (grid min/max) was 0.52–1.44 kg/ton-km; the Monte Carlo 90% interval was 0.67–1.02 kg/ton-km, which lay well inside the envelope because the triangular draws concentrated near the baseline-aero mode rather than reaching the grid corners.

2.5. Direct Operating Cost Model

The direct operating costs (DOCs) were decomposed into fuel, maintenance, crew, fees, and capital recovery:

$$DOC = C_{\text{fuel}} + C_{\text{maint}} + C_{\text{crew}} + C_{\text{fees}} + C_{\text{capital}}, \quad (8)$$

where the five components are defined, in turn, below. **Fuel.** The fuel cost equaled the block fuel from Equations (1)–(3) multiplied by the Jet-A price. We used \$0.80/kg for both modes, set from the EIA U.S. Gulf Coast kerosene-type jet fuel spot price (2019–2023 mean, expressed in 2022 USD) [27]. The base case applied *no* supersonic procurement premium ($p_{\text{sup}} = 0$); instead, smaller-volume procurement, boutique logistics, or SAF blending was captured through the $\pm 50\%$ fuel-price sensitivity (Section 2.6) rather than a fixed surcharge, which avoided encoding an unverifiable premium into the headline result.

Maintenance. Maintenance was modeled as rate $\times$ block time. The subsonic rate (\$180/h per functional ton) was anchored to ICAO per-block-hour operating-cost categories (whose maintenance line runs to several hundred dollars per block hour for passenger jets), normalized to a per-functional-ton basis and inflated from the ICAO base year (late-1990s–early-2000s U.S. airline data) to 2022 USD using the U.S. CPI-U [28,29]. The supersonic rate (\$1000/h per functional ton) carries a maintenance premium anchored to legacy SST operating-cost studies [30,31]. On a per-functional-ton basis this is a large multiple of the subsonic rate, because the supersonic airframe spreads specialized, thermally driven maintenance over a much smaller payload (5–10 t versus ~ 100 t). Separately, those legacy studies place the *whole-aircraft* supersonic maintenance premium at a multiplier of order $k_{\text{sup}} \approx 2$ (range 1.5–3.0) relative to a comparable subsonic airframe; this whole-aircraft premium and the per-functional-ton rates above are distinct normalizations (per airframe versus per functional ton) and are not a single arithmetic identity, so we carried k_{sup} only as an uncertainty band rather than a calibrated value, given the well-known bias in 1960s–1970s SST cost transfers. Note that k_{sup} was not itself a sampled Monte Carlo variable; the *cost* uncertainty propagation sampled only fuel price and load factor (Table 1), with the maintenance and capital rates held fixed, so the reported DOC intervals held the maintenance multiplier constant.

Crew and fees. The crew costs assumed piloted two-person flight decks; we applied total cockpit costs of \$300/h (subsonic)—of the same order as ICAO per-block-hour passenger

crew costs, adjusted downward for a cargo flight deck [28]—and \$500/h (supersonic). The 67% supersonic uplift was an explicit modeling assumption—reflecting type-rating scarcity, recurrent high-speed training, and hazard pay rather than a benchmarked figure; however, because crew is a minor component of a DOC dominated by maintenance and capital, this assumption did not materially affect the supersonic DOC ranking. (A fully autonomous supersonic concept would lower this line; that variant was outside the scope of the piloted first-generation baseline analyzed here.) The fees incorporated landing, navigation, and handling charges (\$350 supersonic, \$150 subsonic per mission) and did not scale with block time; both per-mission values were the authors' assumptions of representative magnitudes rather than figures taken from a published charge schedule, and the supersonic value was perturbed by $\pm 50\%$ in the sensitivity analysis. To make the normalization explicit: maintenance and capital entered as *per-functional-ton* rates (airframe cost spread over each mode's payload capacity), whereas crew (per block hour) and fees (per mission) were whole-aircraft charges applied in full to the 1-ton functional unit. The *allocation rule* is identical for both aviation modes, but because the modeled payload capacities differed sharply (5–10 t supersonic versus ~ 100 t subsonic) its *effect* was deliberately not symmetric: charging the full per-mission and per-block-hour amounts to a single costed ton weighed more heavily on the small-payload supersonic case than on the subsonic one. Taken on its own, this cost-allocation asymmetry inflated the supersonic DOC premium relative to what a payload-matched allocation would yield, so the DOC line, considered in isolation, was an upper-leaning estimate. This is only one of several biases the analysis carried; Section 2.7 catalogs the full set, and on balance the dominant biases there (climate metrics, DOC scope, utilization) acted in the opposite direction, leaving the central conclusions conservative overall. We keep the per-ton and whole-aircraft components separate here, rather than blending them into a single effective rate, precisely so that each can be audited independently (Table 2 for capital; the full cost decomposition is reported in the Results).

Capital and reserves. Capital recovery and reserves used the annuitized aircraft cost per block hour. The annual capital charge was $C_{\text{cap,ann}} = A (C_{\text{acq}} - C_{\text{res}}) + i C_{\text{res}}$, with capital recovery factor $A = i(1+i)^n / [(1+i)^n - 1]$, real cost of capital $i = 8\%$, economic life $n = 20$ years, and residual value $C_{\text{res}} = 0.15 C_{\text{acq}}$. At 3500 block-h/year, a US\$200M supersonic airframe spread over a representative 5–10 t payload (≈ 7.8 t, Table 2) yielded \$720/h per functional ton, and a US\$140M widebody freighter (~ 90 t representative, Table 2) on identical terms yielded \$44/h (worked derivation in Table 2). Block times were derived consistently from true cruise airspeed at the stated Mach ($M = 1.8$ supersonic, $M = 0.80$ subsonic) evaluated at the International Standard Atmosphere (ISA) speed of sound of the isothermal layer ($a \approx 295$ m/s, valid for both modes since the subsonic freighter cruises near the tropopause and the supersonic cruises in the lower stratosphere, both within the 11–20 km isothermal band), plus a symmetric 0.25 h taxi/ground allowance applied to both modes, giving 1.03 h (supersonic) and 2.02 h (subsonic) at 1500 km; dividing the DOC by payload-distance yielded cost intensities. If early supersonic operations are constrained to ~ 1800 h/year, the capital/reserve line rises by roughly 90%, increasing the total DOC by about 23%.

The per-functional-ton capital rates were derived from these primitive assumptions, not assumed: for $i = 0.08$, $n = 20$ the recovery factor was $A = 0.1019$; dividing the resulting annual charge by utilization (3500 block-h/year) gave a whole-aircraft \$/h, which was then spread over the payload capacity to obtain the per-functional-ton rate. Table 2 shows this derivation for both aviation modes.

Table 1. Monte Carlo inputs and distributions (1500 km baseline).

Variable	Distribution	Parameters	Sampling Scope
Mach	Triangular	min 1.6, mode 1.8, max 2.2	Independent draw
L/D	Triangular	min 6.0, mode 7.0, max 8.0	Independent draw
SFC (mg/(N·s))	Triangular	min 20, mode 27.5, max 35	Independent draw
Supersonic EI _{NO_x}	Uniform	15–25	Independent draw
Subsonic EI _{NO_x}	Uniform	8–20	Independent draw
Trucking EI _{NO_x}	Uniform	10–20	Independent draw
Shipping EI _{NO_x}	Uniform	50–100	Independent draw
Rail EI _{NO_x}	Uniform	30–60	Independent draw
Subsonic CO ₂ EF	Normal	mean 0.545, sd 0.015, clip 0.45–0.65	Independent draw
Fuel price (Jet-A)	Trunc. normal	mean \$0.80/kg, sd 20%, trunc. $\pm 50\%$	Common to both modes
Load factor	Triangular	min 0.50, mode 0.70, max 0.85	Common to both modes

Notes: All NO_x emission indices (EI) are in g/kg fuel, and the subsonic CO₂ emission factor (EF) is in kg/ton-km. The fuel-price mean (\$0.80/kg) is the EIA Gulf Coast jet-fuel spot series in 2022 USD [27]; “Trunc. normal” is a truncated normal distribution, and “clip” denotes hard truncation of the sampled values. EI ranges reflect literature scatter; independence from SFC is a simplifying assumption that may understate tail risk if inefficient engines also exhibit higher EI. Stage length is fixed at 1500 km for Monte Carlo outputs; deterministic stage-length sensitivity is reported separately. The load-factor draw is the cost-spreading divisor defined in Section 2.2 (the filled fraction of the costed 1-ton functional unit, applied to the DOC only), not aircraft payload-capacity utilization.

To make the epistemic status of each cost input auditable at a glance, Table 3 classifies every DOC input as literature-derived (L), authors’ assumption (A), or a model-computed quantity (M); hybrid entries (L+A) denote literature anchors that we normalized or inflated ourselves.

Table 2. Capital-recovery-factor derivation of the per-functional-ton capital rates.

Mode	Payload (t)	Airframe (US\$M)	$C_{cap,ann}$ (US\$M/yr)	Whole-Aircraft (\$/h)	Per-ton (\$/h)
Supersonic	5–10 (≈ 7.8)	200	19.7	5633	720
Subsonic	~ 90 –100 (≈ 90)	140	13.8	3943	44

Notes: Inputs $i = 8\%$, $n = 20$ yr, residual fraction $r = 0.15$, utilization 3500 h/yr. The Airframe and $C_{cap,ann}$ columns are in millions of US dollars (US\$M). The large per-functional-ton gap (\$720 versus \$44) reflects both higher airframe cost (US\$200M versus US\$140M) and much smaller payload capacity: the subsonic freighter spreads a comparable annual charge over $\sim 12\times$ the payload tonnage. Maintenance rates (above) scale with assumed higher thermal and structural loads for supersonic, anchored to legacy SST cost studies [30,31] and inflated via CPI-U [29]. Lower utilization (1800 h/yr) raises the capital line by $\sim 90\%$ and total supersonic DOC by $\sim 23\%$.

The surface-mode DOCs were built from representative per-mission cost components adopted by the authors (classified A in Table 3). To keep costs consistent with the emissions model, each surface fuel line was derived from that mode’s combustion CO₂ (divided by 3.16 kg CO₂/kg fuel) priced at \$400/ton heavy fuel oil (shipping) or \$1.10/kg diesel (trucking and rail); the non-fuel components were the authors’ representative values itemized below. For the 1-ton functional unit the attributable fuel burn was small—a few kilograms for shipping, roughly a dozen for rail, and about 38 kg of diesel for trucking—so fixed handling and access charges still dominated the per-ton surface cost. Shipping costs summed fuel (\$2), maintenance (\$5), crew (\$18), port fees (\$22), and capital (\$10) per mission. Trucking used long-haul diesel assumptions scaled to the 1-ton functional unit: fuel (\$42), maintenance (\$25), driver (\$60), road fees/tolls (\$20), and capital/reserves (\$25). Rail combined fuel/traction energy (\$14), maintenance/overhead (\$30), crew (\$35), track access/fees (\$45), and capital/reserves (\$15). The resulting cost intensities were \$0.04/ton-km (shipping), \$0.11/ton-km (trucking), and \$0.09/ton-km (rail). These values

were evaluated at the 1500 km baseline mission. At the other stage lengths, the time- and distance-based components (fuel, maintenance, crew or driver, and capital) scaled approximately linearly with distance while the per-mission access charges (road tolls, port fees, track access) remained fixed, giving the surface modes the same—though far milder— $1/d$ intensity shape as the aviation fixed overheads: approximately \$0.14/ton-km (500 km) to \$0.11/ton-km (5000 km) for trucking, \$0.15 to \$0.07/ton-km for rail, and \$0.07 to \$0.03/ton-km for shipping. The one-to-two-order-of-magnitude cost gap between surface modes and aviation therefore persisted at every stage length examined; these trajectories are tabulated alongside the surface-mode CO₂ values in Section 3.3.

Heterogeneity within surface modes is large. The factors above correspond to feeder/container operations (shipping), long-haul heavy-duty diesel trucks, and conventional diesel freight rail. Deep-sea ships and electrified rail can achieve lower intensities; smaller vessels or short-haul trucks running partly empty can increase intensities by tens of percent. Shipping CO₂ intensities vary strongly with vessel class and operating profile: within a ship type, mean carbon intensity per ton-km decreases markedly with ship size, and the ship-to-ship interquartile spread within a size category is typically 20–50% of the median for container ships and 30–80% or more for other cargo ship types; it is generally wider for smaller vessels, per the ship-type carbon-intensity estimates of the Fourth IMO GHG Study 2020 (its Section 3.3.1 and Tables 59–61) [19]; operational measures—notably speed and voyage optimization adopted for compliance with the IMO’s Carbon Intensity Indicator (CII), in force since 2023—can shift in-service intensities further [17]; rail can drop materially under high grid decarbonization. These variations do not close the order-of-magnitude gap to aviation but bracket the surface-mode baselines used here.

2.6. Uncertainty and Sensitivity Analysis

Uncertainty was propagated via 10,000-sample Monte Carlo draws, following established inventory-uncertainty guidance [32]. For emissions, EI bounds defined uniform distributions; the supersonic aerodynamic parameters followed triangular distributions centered on baseline values ($M = 1.8$, $L/D = 7.0$, $SFC = 27.5 \text{ mg}/(\text{N}\cdot\text{s})$) with minima/maxima equal to the grid limits. Mach, L/D , and SFC were sampled independently. Because the triangular draws concentrated near the modal (baseline) values, the resulting Monte Carlo interval was narrower than the full grid envelope; we therefore report the scenario envelope (grid min/max) alongside the Monte Carlo bounds as the more conservative measure of spread. Independent sampling also permits jointly extreme-favorable combinations (e.g., simultaneously high L/D and low SFC) that a physically coupled design is unlikely to achieve, so the favorable (low) tail of the Monte Carlo interval should be read as optimistic. Fuel price was modeled as a single truncated-normal draw *common to both modes* (so the mode-relative cost gap was driven by fuel *burn*, not by a price differential): mean \$0.80/kg from the EIA spot-price series, standard deviation 20% of the mean, hard-truncated at $\pm 50\%$ of the mean. The load factor was sampled between 0.5 and 0.85 (triangular, mode 0.7) to translate the DOC to cost per carried ton. Stage-length sensitivity was evaluated deterministically using the fixed-overhead structure described earlier; the reported intervals were therefore conditional on the 1500 km baseline. A value-of-time threshold was computed as

$$\text{VOT}_{\text{break-even}} = \frac{\Delta \text{DOC} / m_{\text{payload}}}{\Delta t}, \quad (9)$$

where ΔDOC is the supersonic-minus-subsonic DOC difference for the same payload and stage length, m_{payload} is the payload mass defined in Section 2.1, and Δt is the difference in block time between supersonic and subsonic missions (0.98 h for the 1500 km baseline, computed from unrounded block times; the rounded values 1.03 h and 2.02 h differed by

0.99 h). To attribute the Monte Carlo spread to its sources, we additionally decomposed the variance of each sampled output by input parameter using squared Spearman rank correlations between the input draws and the output, normalized to sum to one, and we cross-checked them against binned first-order Sobol' indices computed from the same 10,000 draws [33], since squared rank correlations recover first-order variance shares reliably only for monotonic input–output relationships; because the inputs were sampled independently, these first-order shares captured essentially the full output variance (the raw squared correlations summed to 0.98–0.99). The percentile results (5th/50th/95th) and this variance decomposition are reported in the Results section and are reproducible with the accompanying code repository (see Data Availability).

Table 3. Provenance of direct operating cost inputs: literature-derived (L), authors' assumption (A), or model-computed (M).

Input	Value	Basis	Source/Derivation
Jet-A price	\$0.80/kg	L	EIA Gulf Coast spot series, 2019–2023 mean in 2022 USD [27].
Block fuel	mode-specific	M	Emissions model and Breguet grid (Sections 2.3 and 2.4).
Block time	2.02 h/1.03 h	M	Cruise-speed method (this section).
Maintenance rate	\$180/\$1000 per h per functional ton	L+A/A	Subsonic: ICAO block-hour cost categories, CPI-U-inflated and per-ton-normalized by the authors [28,29]; supersonic: assumption anchored to legacy SST cost studies [30,31].
Crew rate	\$300/\$500 per h	L+A/A	Subsonic: order of ICAO block-hour crew costs, adjusted for a cargo flight deck [28]; supersonic: explicit 67% uplift assumption (this section).
Fees per mission	\$150/\$350	A	Authors' assumption of representative per-mission landing, navigation, and handling charges (this section); supersonic uplift assumed.
Airframe price	US\$140M/US\$200M	A	Representative values (Table 2).
Capital primitives	$i = 8\%$, $n = 20$ yr, residual 15%, 3500 h/yr	A	Stated financing and utilization assumptions.
Capital rate per functional ton	\$44/\$720 per h	M	Capital-recovery derivation (Table 2).
Payload capacity	≈ 90 t/ ≈ 7.8 t	A+M	B777F-class benchmark; volumetric estimate (Section 2.1).
Fuel-price spread; load factor	Table 1	A	Monte Carlo distributions (Section 2.6).

Notes: Paired values are quoted subsonic/supersonic. L denotes a value taken from a published source; A denotes an authors' modeling assumption (with its stated anchor where one exists); M denotes a quantity computed inside the model from L/A inputs. Surface-mode DOC components (below) are representative values adopted by the authors (A), except each mode's fuel line, which is model-computed (M) from its combustion CO₂.

2.7. Limitations and Scope

This subsection expands the three “screening-level” simplifications defined at the start of Section 2 into specific choices, and for each states the likely *direction* of bias and, where it can be bounded, its approximate *magnitude*, so a decision-maker can judge whether the findings are conservative or optimistic. Mission performance uses a steady-cruise Breguet formulation with fixed overheads; the DOC uses stylized, transparently sourced capital/maintenance inputs rather than operator ledgers; and the quantitative climate metrics report mass emissions only, with effective radiative forcing entering solely through a single illustrative ERF/CO₂e bound in the Discussion.

- **Climate metrics (bias: understates supersonic disadvantage; literature ERF/CO₂-only ratio $\sim 2\text{--}3\times$):** Results are mass emissions; ERF/CO₂e, NO_x-ozone chemistry, and contrail-cirrus forcing [34,35] are excluded, so the $2.30\times$ CO₂ penalty is a lower bound on climate impact [10,36]. ERF-based assessments suggest total forcing for high-altitude aviation can be $\sim 2\text{--}3\times$ CO₂-only forcing (the same ratio cited above), with supersonic cruise likely at the upper end because of stratospheric NO_x and

H₂O [12,37]; the Discussion (Section 4) translates this into an illustrative CO₂e estimate, keeping the literature ratio distinct from the multiplier applied to supersonic cruise alone and from the resulting comparison ratios.

- **Emission indices (bias: understates NO_x tail risk):** EIs are constant and independent of SFC/altitude due to lack of OPR-resolved data. Because thermal-NO_x formation tends to rise with the same high combustor temperatures that worsen SFC, the independence assumption populates the “low-SFC, low-NO_x” tail with physically unlikely engine cycles and likely makes the upper bound for NO_x too narrow. CO₂, by contrast, is governed by the SFC and L/D draws rather than by the EI-independence assumption, so its bounds are unaffected by this particular simplification.
- **Trajectory and routing (bias: direction unclear, second-order):** Supersonic performance uses steady-cruise Breguet; climb/descent optimization and low-boom routing detours are not modeled, which could shift intensities in either direction but is small relative to the SFC/L/D spread.
- **Payload/volume (bias: favors supersonic if the volumetric bay cannot be filled):** Early cargo concepts likely support 5–10-ton payloads based on volumetric scaling of slim fuselages (Section 2.1); low-density cargo that cannot fill the bay would raise \$/ton-km and kg/ton-km, worsening the supersonic case.
- **System boundaries (bias: symmetric across modes within tank-to-wake; ERF asymmetry treated separately):** Emissions are tank-to-wake only; upstream fuel production and infrastructure are outside scope (ERF/CO₂e is treated separately under the climate-metrics item above, where its omission is the asymmetric bias that understates the supersonic disadvantage). Costs are the operational DOCs (fuel, crew, maintenance, fees, capital/reserves) and exclude R&D, infrastructure, and network effects. To keep the comparison fair, infrastructure is excluded symmetrically: airport and port/terminal infrastructure are both omitted, and surface-mode capital covers vehicles only. This aligns with operational (non-LCA) boundaries in [14].
- **DOC scope (bias: understates supersonic cost):** Network effects (fleet mix, repositioning), carbon pricing, insurance, and supersonic-specific regulatory fees are omitted, all of which would more plausibly raise than lower the supersonic premium; capital/maintenance inputs are stylized (Table 2).
- **Utilization (bias: understates supersonic cost if low):** Baseline uses 3500 h/year; lower utilization increases the supersonic capital burden, as quantified in Section 2.5.

Ranked by leverage on the headline ratios, the leading uncertainties are: (i) engine SFC feasibility (the dominant one-at-a-time driver, $\pm 40\%$); (ii) non-CO₂ climate effects (a $\sim 2\text{--}3\times$ ERF amplification excluded from the mass-emissions headline); (iii) load factor and annual utilization (load factor 0.5–0.85 raises the delivered-ton cost, and 1800 h/year utilization raises the capital line by $\sim 90\%$ and total DOC by $\sim 23\%$); (iv) operational and network economics (fleet mix, repositioning, and demand, unquantified and outside the DOC scope); and (v) aerodynamic performance (L/D, $\pm 20\%$). On balance, the dominant biases (climate metrics, DOC scope, utilization) all act to *understate* the supersonic penalty, so the central conclusions are conservative. Future work will integrate mission simulations with ERF-based climate metrics, building on the code released with this paper (see Data Availability).

3. Results

3.1. Emissions Comparison

We present the modal comparison in stages: the 1500 km baseline (Table 4, Figure 1), the stage-length dependence (Table 5), a concrete lane illustration, and the Monte Carlo uncertainty distributions (Figure 2, Table 6). Table 4 and Figure 1 present the calculated emissions for the 1-ton, 1500 km baseline mission, combining the fuel-based combustion

model with literature emission indices (NO_x) and surface-mode inventory factors. The parenthetical NO_x ranges spanned the full literature EI bounds for each mode (Section 2.3), while H_2O followed directly from stoichiometry. The conservative (first-generation) supersonic case emitted $2.30\times$ the CO_2 of the subsonic aircraft (1.25 versus 0.545 kg/ton-km) and roughly three times the NO_x mass. The scenario envelope spanned 0.52–1.44 kg/ton-km (about $0.96\text{--}2.64\times$); the Monte Carlo 90% interval was tighter at 0.67–1.02 kg/ton-km (about $1.23\text{--}1.87\times$). The supersonic and subsonic CO_2 distributions were essentially disjoint over their 90% intervals: the supersonic 5th percentile (0.67 kg/ton-km) exceeded even the subsonic 95th percentile (0.57 kg/ton-km), so all but the most extreme supersonic draws remained more carbon-intensive than a typical subsonic mission. Shipping and rail remained one to two orders of magnitude lower in CO_2 , and trucking sat between those surface modes and air freight. Surface-mode efficiency came at the expense of transit time; the relevant counterfactual for urgent freight was subsonic air, with trucking appropriate mainly for shorter-haul cases.

Table 4. Calculated emissions for 1-ton, 1500 km mission with emission intensities.

Mode	CO_2		NO_x		H_2O	
	kg	kg/ton-km	kg	kg/ton-km	kg	kg/ton-km
Supersonic	1881	1.25	11.9 (8.9–14.9)	0.01	732	0.49
Subsonic	818	0.545	3.9 (2.1–5.2)	<0.01	318	0.21
Trucking	120	0.08	0.60 (0.40–0.80)	<0.01	47	0.03
Shipping	15	0.01	0.33 (0.24–0.47)	<0.01	6	<0.01
Rail	40	0.0265	0.50 (0.38–0.76)	<0.01	15	0.01

Notes: NO_x calculated using emission indices (g/kg fuel): subsonic 15 (8–20), supersonic 20 (15–25), trucking 15 (10–20), shipping 70 (50–100), rail 40 (30–60); aviation indices from [18]; surface-mode NO_x indices from the EMEP/EEA Air Pollutant Emission Inventory Guidebook [22] (road 1.A.3.b, navigation 1.A.3.d, railways 1.A.3.c), with adopted values within the guidebook’s reported ranges. H_2O from stoichiometry (1.23 kg/kg fuel). Fuel burn derived from CO_2 (3.16 kg CO_2 /kg fuel; applies to kerosene, diesel, and heavy fuel oil, which share an ~85–86% carbon mass fraction). Trucking CO_2 factors use long-haul diesel freight guidance [14]. Only NO_x carries a range (parenthetical), spanning the full literature EI bounds for each mode; CO_2 and H_2O are deterministic point values at the baseline configuration. Calculations and data reproducible with the accompanying code repository (see Data Availability).

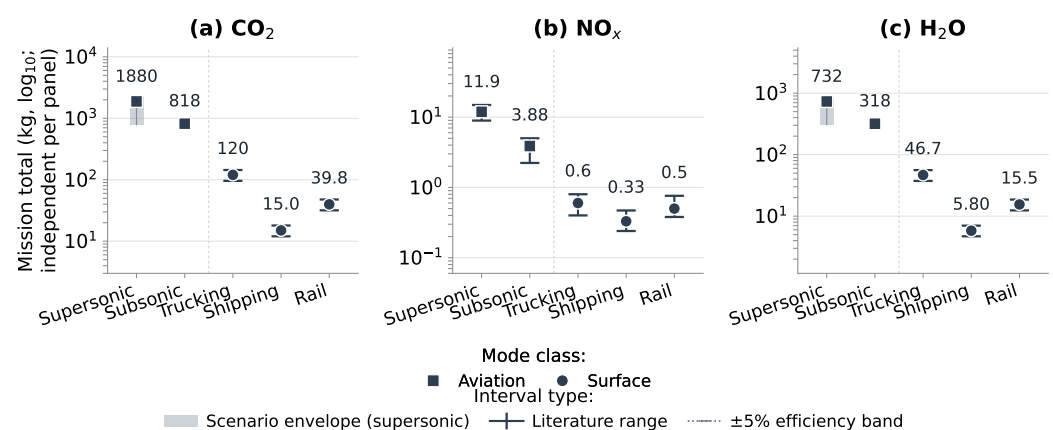


Figure 1. Mission-total CO_2 , NO_x , and H_2O emissions (kg) for a 1-ton payload carried 1500 km, plotted on independent $\log_{10}$ y-axes per panel. Square markers denote aviation, circles denote surface modes; supersonic uses the conservative first-generation scenario (Table 4). The three interval types encode different uncertainty sources—scenario envelope (supersonic CO_2 and H_2O), literature range (every NO_x panel and all surface modes), and $\pm 5\%$ efficiency band (subsonic CO_2 and H_2O)—so interval lengths are interpretable only against intervals of the same type, never across types. Per-ton-km intensities follow by dividing the plotted values by 1500.

The stage-length sensitivity for the two aviation modes is summarized in Table 5. Fixed fuel overheads amplified CO₂ intensity for short missions: supersonic transport reached 1.72 kg/ton-km at 500 km (compared with 1.25 kg/ton-km at 1500 km), whereas long-haul missions diluted the penalty to roughly 1.09 kg/ton-km at 5000 km. *Model scope note:* this table fixes block fuel as a constant cruise rate plus the fixed mission overhead, so intensity decreases monotonically with distance once the overhead is amortized; the upturn at long range visible for the conservative configuration in the value-of-time analysis of the Discussion arises instead from re-solving the full Breguet weight equation, which lets fuel fraction grow with distance until the weight-limited maximum range is reached. Both treatments are reported because they answer different questions: the constant-cruise model describes a given technology level deployed on aircraft sized for each mission, which is the relevant basis for the cross-modal comparison at fixed payload, whereas only the fixed-airframe Breguet re-run resolves the weight-limited stage length required by the value-of-time analysis. Quantitatively, the two treatments coincided at the 1500 km calibration point by construction; at 500 km the constant-cruise model was the more penalizing of the two for the supersonic case (1.72 versus ≈ 1.5 kg/ton-km from the fixed-airframe re-solve), so the short-haul conclusions were conservative under either treatment; and at 5000 km the fixed-airframe re-solve escalated well above the tabulated value (≈ 6.5 versus 1.09 kg/ton-km) as the conservative configuration approached its ≈ 5500 km weight-limited maximum range, so the 5000 km entry should be read as a design-range-matched technology projection rather than as a 1500 km-class airframe stretched to long haul. Under either reading the qualitative conclusions are unchanged: short missions were penalized most, and supersonic intensity remained well above the subsonic benchmark at every distance examined. The subsonic aircraft exhibited a similar but less pronounced pattern (0.71 kg/ton-km at 500 km); the sensitivity of these short-haul intensities to the assumed overhead magnitude is quantified in Table 7, which varies the fixed overhead by -25% and $+50\%$. These CO₂ values translate to block fuels of 272–1726 kg (supersonic) and 112–774 kg (subsonic) across the stage lengths. The DOC block times (1.03 h supersonic, 2.02 h subsonic) are defined for the 1500 km baseline only; the stage-length fuel results are decoupled from those cost block-time assumptions. Trucking, shipping, and rail retained constant CO₂ intensities within the distances examined due to near-linear fuel scaling, so the surface-mode intensities of Table 4 applied unchanged at 500 and 5000 km: trucking remained at 0.080 kg/ton-km (mission totals of 40 and 400 kg CO₂), rail at 0.0265 kg/ton-km (approximately 13 and 133 kg), and shipping at 0.010 kg/ton-km (5 and 50 kg). The aviation–surface CO₂ gap was therefore widest at 500 km, where the aircraft fixed overheads weighed most heavily; the corresponding stage-length behavior of the surface-mode cost intensities is given in Section 2.5, and Table 8 (Section 3.3) consolidates the surface-mode CO₂ and cost intensities at all three stage lengths.

Translating these aggregate results to a concrete lane illustrates the trade-off. For a 1-ton urgent pharmaceutical shipment from Los Angeles to New York (~ 3900 km), subsonic air delivers in a ~ 4.8 h block with ~ 0.50 kg/ton-km CO₂. A first-generation supersonic would instead cut block time to ~ 2.3 h but raise intensity to ~ 1.11 kg/ton-km (conservative scenario). The block times follow the same cruise-speed method as the baseline (Section 2.5): cruise speeds of $V \approx 236$ and 531 m/s at the subsonic and supersonic cruise Mach, plus the symmetric 0.25 h taxi allowance, give ~ 4.8 h and ~ 2.3 h at 3900 km. These values are obtained by evaluating the fixed-overhead-plus-cruise intensity model (Equation (2)) directly at 3900 km—the fixed CO₂ overhead contributes $350/(1 \times 3900) \approx 0.09$ kg/ton-km on top of the cruise term—rather than by linear interpolation, since the intensity varies as $1/d$. Rail or trucking would be far lower in CO₂ but entail multi-day transit over this transcontinental lane, versus a 24–48 h transit window adopted here as a working

requirement for urgent cold-chain cargo; shipping is not a substitute for urgent cold-chain cargo. The lane therefore makes concrete the general finding: among the modes considered, the only alternative within the 24–48 h cold-chain window for this urgent cargo is subsonic air, against which supersonic carries a $\sim 2.2\times$ CO₂ penalty on this 3900 km lane. This is slightly narrower than the $2.30\times$ headline ratio at the 1500 km baseline because the supersonic overhead (350 versus 120 kg) amortizes faster relative to its larger cruise term as distance grows.

Sampling the supersonic parameter grid with Monte Carlo uncertainty (triangular distributions on Mach, L/D, SFC centered on the baseline) yielded a 90% interval CO₂ intensity of 0.67–1.02 kg/ton-km (Table 6); the full scenario envelope extended from 0.52 to 1.44 kg/ton-km. This near-threelfold envelope width (max/min $\approx 2.8\times$) was a deterministic grid min/max spanning the corner cases, not a statistical interval; it was driven primarily by SFC ($\pm 40\%$ one-at-a-time), with L/D ($\pm 20\%$) and Mach ($\pm 15\%$) secondary, and the Monte Carlo interval was narrower because the triangular draws concentrated near the baseline-aero mode rather than at the grid corners. The conservative 1.25 kg/ton-km value lay above the MC 95th percentile, reflecting its origin as a bounding scenario rather than a central estimate. Throughout the paper, all CO₂ ratios—including the Monte Carlo percentile ratios—were computed directly from the corresponding intensities; the label *indicative* applies only to the DOC ratios of the non-headline scenarios summarized in the Discussion, which were evaluated at the baseline cost inputs rather than independently re-computed. The DOC distributions were likewise well separated: the supersonic 5th percentile (\$2.5/ton-km) sat above the subsonic 95th percentile (\$1.7/ton-km), so under the sampled fuel-price and load-factor variation there was no overlap between modes in cost intensity. Panel (c) of Figure 2 shows the relative CO₂ sensitivity weights (SFC ≈ 0.48 , L/D ≈ 0.26 , Mach ≈ 0.26), confirming SFC as the primary driver with L/D and Mach comparable and secondary. These weights and the $\pm 40\%/\pm 20\%/\pm 15\%$ figures in Table 9 are two normalizations of the same one-at-a-time sweep—the weights rescaled to sum to one, the percentages left as raw fractional changes—so they differ in value but agree that SFC was the dominant lever, with L/D and Mach close and secondary. A variance decomposition of the Monte Carlo output itself sharpens this ranking: normalized squared rank correlations attribute about 62% of the supersonic CO₂-intensity variance to SFC, 21% to Mach, and 17% to L/D (binned first-order Sobol' indices agree to within two percentage points; Mach edges above L/D here—the reverse of the one-at-a-time ordering—because its triangular support spans a wider fraction of its mode, $-11\%/+22\%$ around the 1.8 mode versus $\pm 14\%$ for L/D, so the Mach draws carry more relative dispersion into the sampled variance), while the supersonic DOC variance is dominated by load factor ($\approx 95\%$), with fuel price ($\approx 3\%$) and the aerodynamic draws (jointly $<2\%$, entering through block fuel) minor—consistent with the fixed maintenance and capital rates noted in Table 6. The decomposition also makes explicit what the favorable tail requires technologically: in the most favorable 5% of CO₂ draws the mean SFC is 22.7 mg/(N·s) (versus the 27.5 mode), the mean L/D is 7.3, and the mean Mach is 2.0, and about 70% of those draws combine all three favorable deviations simultaneously—so the lower bound of the 90% interval represents a jointly optimistic engine-plus-airframe outcome rather than the reach of any single parameter, reinforcing the caveat in Section 2.6 that the low tail should be read as optimistic.

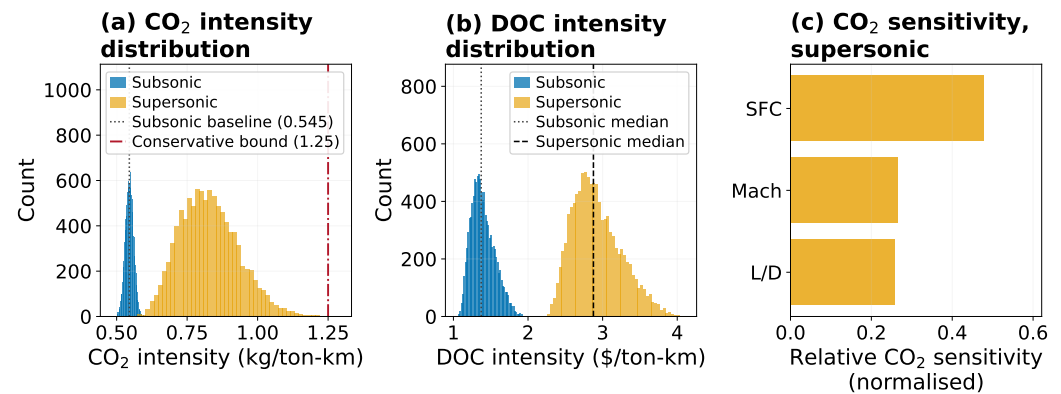


Figure 2. Monte Carlo uncertainty visualization for a 1-ton payload over 1500 km. Panels (a,b) show the CO₂ and DOC intensity distributions for the subsonic and supersonic cases; panel (c) shows the relative one-at-a-time (OAT) CO₂ sensitivity weights for the supersonic case, with SFC the dominant driver and L/D and Mach comparable and secondary. N = 10,000 Monte Carlo samples; 5th/50th/95th percentile values are listed in Table 6.

Table 5. Stage-length sensitivity for supersonic and subsonic aircraft (mid-range EI values).

Distance (km)	Supersonic				Subsonic			
	CO ₂ (kg)	kg/ton-km	NO _x (kg)	H ₂ O (kg)	CO ₂ (kg)	kg/ton-km	NO _x (kg)	H ₂ O (kg)
500	860	1.72	5.44	335	353	0.71	1.67	137
1500	1881	1.25	11.90	732	818	0.545	3.88	318
5000	5453	1.09 [†]	34.51	2122	2445	0.49	11.61	952

Notes: Values derived from fixed CO₂ overheads (350 kg supersonic, 120 kg subsonic) plus distance-proportional cruise fuel. NO_x computed using representative central EI values (20 g/kg supersonic, 15 g/kg subsonic; rounded literature central values rather than exact bracket midpoints); H₂O equals 1.23 × fuel burn. Intensities exclude contrail-induced radiative forcing. The optimistic scenario after overhead is 0.59 kg/ton-km; the conservative (first-generation) scenario underpins all main comparisons. [†] The 5000 km supersonic entry is a design-range-matched technology projection (constant cruise factor; aircraft sized for each mission), not a 1500 km-class airframe stretched to long haul: re-solving the full Breguet weight equation for a fixed 1500 km-class airframe instead yields ≈1.5 kg/ton-km at 500 km, 1.25 kg/ton-km at 1500 km (the calibration point, by construction), and ≈6.5 kg/ton-km at 5000 km as the conservative configuration approaches its ≈5500 km weight-limited maximum range (model scope note above).

Table 6. Monte Carlo 5th/50th/95th intensities for 1500 km baseline.

Mode	CO ₂ (kg/ton-km)			DOC (\$/ton-km)		
	5th	50th	95th	5th	50th	95th
Supersonic	0.67	0.82	1.02	2.5	2.9	3.5
Subsonic	0.52	0.55	0.57	1.2	1.4	1.7

Notes: Percentiles from 10,000-sample Monte Carlo. Supersonic CO₂ percentiles come from triangular draws on Mach/L/D/SFC; subsonic CO₂ shows only a narrow 5th–95th spread (0.52–0.57) because it is modeled as a fixed block emission factor (0.545 kg/ton-km) plus a small efficiency uncertainty ($\sigma \approx 0.015$ kg/ton-km), with the emission-index draws affecting NO_x rather than CO₂ or the DOC. The scenario envelope (0.52–1.44 kg/ton-km) spans the full deterministic grid; the MC 90% interval shown here is narrower because triangular draws concentrate near the mode. DOC quantiles reflect fuel-price (±50%) and load-factor (0.5–0.85) variability common to both modes; maintenance/capital uncertainty is treated separately.

Table 7. Sensitivity to mission overhead assumptions (500 and 1000 km cases).

Mode	Distance (km)	Overhead Scaling	CO ₂ (kg)	kg/ton-km
Supersonic	500	−25% overhead (262.5 kg)	773	1.55
Supersonic	500	Baseline (350 kg)	860	1.72
Supersonic	500	+50% overhead (525 kg)	1035	2.07
Supersonic	1000	−25% overhead (262.5 kg)	1283	1.28
Supersonic	1000	Baseline (350 kg)	1371	1.37
Supersonic	1000	+50% overhead (525 kg)	1546	1.55
Subsonic	500	−25% overhead (90 kg)	323	0.65
Subsonic	500	Baseline (120 kg)	353	0.71
Subsonic	500	+50% overhead (180 kg)	413	0.83
Subsonic	1000	−25% overhead (90 kg)	555	0.56
Subsonic	1000	Baseline (120 kg)	585	0.59
Subsonic	1000	+50% overhead (180 kg)	645	0.65

Notes: Overhead terms derived from ICAO short-haul block-fuel fractions; mapping shown in Section 2.3. Sensitivity illustrates overhead dominance at short stage length; long-haul results change negligibly.

3.2. Supersonic Performance Parametrics

The supersonic CO₂ intensity in Table 4 is a conservative first-generation estimate. The Breguet implementation, the Mach/L/D/SFC grid, and the three scenario labels (*baseline aero*, *conservative cargo*, *optimistic*) are defined in Section 2.4; here we report only the quantitative outcomes of the grid (Table 9). The 64-node envelope sweep used four evenly spaced levels of each parameter (Mach at 1.6, 1.8, 2.0, 2.2; L/D at 6.0, 6.67, 7.33, 8.0; and SFC at 20, 25, 30, 35 mg/(N·s)), whereas the three named scenarios and the heatmap slices instead used the representative SFC values 20/27.5/35 mg/(N·s) (optimistic/baseline-aero/conservative) as illustrative points rather than grid nodes—so the baseline-aero value (27.5) was deliberately not one of the four sweep levels, nor was the baseline L/D of 7.0.

Table 8. Surface-mode CO₂ and direct operating cost intensities at the three stage lengths (1-ton functional unit).

Mode	CO ₂ (kg/ton-km)	Mission CO ₂ (kg)			DOC (\$/ton-km)		
	All Stage Lengths	500 km	1500 km	5000 km	500 km	1500 km	5000 km
Trucking	0.080	40	120	400	0.14	0.11	0.11
Rail	0.0265	≈13	40	≈133	0.15	0.09	0.07
Shipping	0.010	5	15	50	0.07	0.04	0.03

Notes: This table consolidates, in one place, surface-mode values reported in Sections 2.5 and 3.1; it introduces no new quantities. CO₂ intensities are distance-invariant under the linear surface model (Section 2.1) and equal the intensities of Table 4, so mission totals scale linearly with distance. DOC intensities follow the stage-length allocation rule of Section 2.5 (per-mission access charges fixed; fuel, maintenance, crew or driver, and capital distance-linear) applied to the Table 10 components; the surface 1/d intensity shape is far milder than aviation's, which is why the trucking values at 1500 and 5000 km coincide at the two-decimal precision shown.

The grid had an internal max/min ratio of roughly $2.8\times$ (0.52–1.44 kg/ton-km with overhead) and is visualized as Mach/L/D contours at three SFC levels in Figure 3. The key result is that only the most favorable corner (high Mach, high L/D, low SFC) reached the subsonic benchmark, while the conservative cargo point (1.25 kg/ton-km) sat at $2.30\times$ subsonic; SFC was the dominant lever ($\pm 40\%$), so propulsion efficiency, more than aerodynamics or Mach, governs whether supersonic cargo can ever approach subsonic intensity.

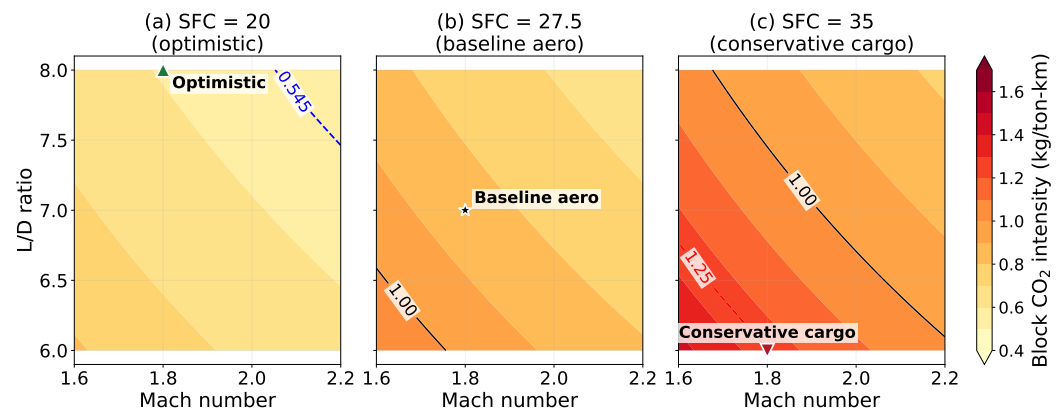


Figure 3. Supersonic parameter-space heatmap showing block CO₂ intensity (kg/ton-km) as a function of Mach number and L/D ratio at three SFC levels (20, 27.5, 35 mg/(N·s)). The blue dashed contour marks the subsonic benchmark (0.545 kg/ton-km), the black solid contour the 1.00 kg/ton-km isoline (a round-number reference between the two), and the red dashed contour the conservative cargo scenario (1.25 kg/ton-km). The heatmap confirms that only the most optimistic L/D and SFC combinations reach subsonic parity.

3.3. Operational Cost Analysis

Table 10 decomposes the DOC (Equation (8)) for the 1500 km mission. The supersonic operations were dominated by maintenance and capital/reserves (57% of the DOC), whereas the subsonic costs were dominated by crew and maintenance. For the supersonic mode, maintenance is the single largest component, with capital/reserves the next largest, partly by construction: the small assumed supersonic payload capacity (5–10 t versus ~100 t subsonic) spread the airframe cost over far less payload per functional ton (Table 2), so a larger supersonic freighter would compress this term and narrow the premium. Because whole-aircraft crew and per-mission fees are likewise charged in full to the single costed ton (Section 2.5), the supersonic DOC intensity (\$2.08 versus \$0.94/ton-km, 2.21×) should be read as an upper-leaning screening estimate on the cost-allocation dimension; the excluded cost items noted at the end of this subsection act in the opposite direction. The surface modes remained far lower: shipping and rail were one-to-two-orders-of-magnitude below aviation, and trucking sat between those surface modes and air freight. The surface-versus-aviation ordering held across all three stage lengths: surface-mode CO₂ intensities were distance-invariant (Section 2.1), and their cost intensities varied only mildly between 500 and 5000 km because the per-mission access charges were amortized over distance (Section 2.5), although trucking and rail swapped rank in cost at 500 km, where rail's higher fixed access charges weighed most; Table 8 consolidates these surface-mode CO₂ and DOC values at all three stage lengths. The Monte Carlo simulations that varied the common fuel price and load factor (0.5–0.85) yielded cost intensities of roughly \$2.5–3.5/ton-km (90% interval, supersonic) and \$1.2–1.7/ton-km for subsonic; these ranges reflect only fuel-price and load-factor variability, with maintenance/capital cost uncertainty explored separately. The \$1710 per ton DOC gap combined with a 0.98 h block-time saving (unrounded) yielded a break-even value-of-time threshold of \$1744/ton-hour for supersonic cargo against subsonic (Equation (9))—roughly 3× the pharma/cold-chain ceiling (\$600/ton-hour) and 6× the express/e-commerce ceiling (\$300/ton-hour). Because the DOC decomposition was additive, the influence of each assumption-based cost input could be isolated exactly; Table 11 perturbs each supersonic cost assumption one at a time over deliberately wide bands. No single-parameter variation brought the supersonic-to-subsonic DOC ratio below 1.84× (the floor corresponded to halving the supersonic maintenance rate), and the ratio was nearly invariant to fuel price (2.20–2.22×) because both modes bought fuel at a common price with similar fuel-cost shares. Even the joint favorable case

that scaled supersonic maintenance and capital rates down by 25–50% together lowered the supersonic DOC by roughly 14–28% (to about \$1.5–1.8/ton-km, i.e., $1.90\text{--}1.58\times$ subsonic) but did not change the qualitative premium. The DOC categories were limited to the modeled components (fuel, maintenance, crew, fees, capital/reserves); items not defined in Section 2.5 such as carbon taxes, insurance, or supersonic-specific regulatory fees were excluded, so the actual costs would likely be higher.

Table 9. Supersonic CO₂ intensity: parametric analysis.

Parameter	Range	Baseline	Sensitivity
Mach number	1.6–2.2	1.8	15%
L/D ratio	6.0–8.0	7.0	20%
SFC (mg/(N·s))	20–35	27.5	40%
Cruise-phase CO₂ intensity (kg/ton-km; ratios versus subsonic block—not like-for-like):			
Minimum (best)	0.29 ($0.53\times$ subsonic)		
Baseline aero (cruise)	0.61 ($1.13\times$ subsonic)		
Maximum (worst)	1.20 ($2.21\times$ subsonic)		
<i>With fixed mission overhead (taxi, take-off, climb, descent, and diversion reserves):</i>			
Adjusted range	0.52–1.44 kg/ton-km ($0.96\text{--}2.64\times$ subsonic)		
Conservative cargo	1.25 kg/ton-km (M = 1.8, L/D = 6.0, SFC = 35)		

Notes: Cruise-phase intensities use the Breguet range equation (1500 km, 1-ton payload, 50,000 ft, OEW/MTOW = 0.52, 5% cruise reserves). Mission-overhead terms (350 kg CO₂ supersonic, 120 kg subsonic) cover taxi, take-off, climb, descent, and diversion reserves and are additive to the 5% cruise contingency, not double-counted. The cruise-phase ratios ($0.53\text{--}2.21\times$) compare cruise-only supersonic intensity against the subsonic block benchmark and are therefore not like-for-like; the like-for-like comparison is the with-overhead range ($0.96\text{--}2.64\times$). The $2.21\times$ maximum cruise-phase CO₂ ratio is numerically coincidental with, and unrelated to, the $2.21\times$ DOC ratio reported in the Discussion. The conservative-cargo variant assumes lower L/D (6.0, for cargo volume) and higher SFC (35, first-generation engines). The **Sensitivity** column is the one-at-a-time fractional change in block CO₂ intensity over each parameter's grid range (SFC $\pm 40\%$, L/D $\pm 20\%$, Mach $\pm 15\%$). Grid-node structure is described in the text above; the full grid is reproducible with the accompanying code repository (see Data Availability).

Table 10. Direct operating cost breakdown for 1-ton, 1500 km mission.

Mode	Fuel (\$)	Maint. (\$)	Crew (\$)	Fees (\$)	Capital (\$)	Total (\$)	\$/ton-km
Supersonic aircraft	476	1034	517	350	745	3123	2.08
Subsonic aircraft	207	363	605	150	89	1413	0.94
Trucking	42	25	60	20	25	172	0.11
Shipping	2	5	18	22	10	57	0.04
Rail	14	30	35	45	15	139	0.09

Notes: Jet-A is priced at \$0.80/kg for both aviation modes (no supersonic premium in the base case) [27]; surface fuels use \$1.10/kg diesel (trucking, rail) and \$400/ton heavy fuel oil (shipping). The cost-allocation basis—per-functional-ton maintenance and capital, whole-aircraft crew and fees applied to the 1-ton unit, and the conservative direction this implies—is defined in Section 2.5; per-ton capital rates are derived in Table 2. The supersonic per-mission capital charge (\$745) is the \$720/h rate over the unrounded block time (shown rounded as 1.03 h). The resulting DOC ratio ($\$2.08/\$0.94 \approx 2.21\times$) is the directly computed headline ratio quoted in the Abstract and consolidated in the Discussion. Components are rounded to the nearest dollar and may not sum exactly to the totals.

Table 11. One-at-a-time sensitivity of the supersonic DOC to assumption-based cost inputs (1500 km, 1-ton functional unit).

Perturbed Input (Baseline)	Variation	Supersonic DOC (\$/ton-km)	DOC Ratio vs. Subsonic
None (baseline)	—	2.08	$2.21\times$
Maintenance rate (\$1000/h per ton)	$\pm 50\%$	1.74–2.43	$1.84\text{--}2.58\times$
Crew rate (\$500/h)	$\pm 50\%$	1.91–2.25	$2.03\text{--}2.39\times$
Per-mission fees (\$350)	$\pm 50\%$	1.97–2.20	$2.09\text{--}2.33\times$
Airframe price (US\$200M)	$\pm 25\%$	1.96–2.21	$2.08\text{--}2.34\times$

Table 11. Cont.

Perturbed Input (Baseline)	Variation	Supersonic DOC (\$/ton-km)	DOC Ratio vs. Subsonic
Real cost of capital (8%)	6–10%	2.00–2.16	2.13–2.30×
Utilization (3500 h/yr)	1800 h/yr	2.55	2.71×
Fuel price (\$0.80/kg, both modes)	±50%	1.92–2.24	2.20–2.22×
Maintenance + capital rates (joint)	−25 to −50%	1.79–1.49	1.90–1.58×

Notes: Each row re-evaluates the additive DOC decomposition of Table 10 with one input perturbed (last row: two inputs, jointly) and all others held at baseline; the subsonic DOC is held fixed except in the fuel-price row, where the common price shifts both modes, which is why that ratio is nearly invariant. Ranges pair the low/high ends of each variation. Values are computed from the unrounded model outputs and are reproducible with the accompanying code repository (see Data Availability).

4. Discussion

The combustion-based emissions modeling shows that the supersonic penalty is primarily driven by propulsion efficiency: relative to the 1500 km subsonic benchmark, the conservative case emitted $2.30\times$ the CO_2 (1.25 versus 0.545 kg/ton-km), with stage-length sensitivity pushing intensities to 1.72 kg/ton-km on short-haul sectors. The scenario envelope spanned 0.52–1.44 kg/ton-km (about $0.96\text{--}2.64\times$); the Monte Carlo analysis tightened the 90% interval to 0.67–1.02 kg/ton-km (about $1.23\text{--}1.87\times$), indicating that only optimistic combinations of L/D and SFC approach parity with advanced subsonic freighters. Shipping and rail remained orders of magnitude lower in CO_2 mass (and substantially lower in NO_x); trucking sat above those surface modes but still far below aviation. While this study reports mass emissions for transparency, aviation's climate impact depends on short-lived forcing from NO_x and contrails; integrating effective radiative forcing metrics is essential before drawing climate-policy conclusions [10,12,36]. The existing ERF literature suggests non- CO_2 effects amplify total forcing by a factor of $\sim 2\text{--}3$ relative to CO_2 -only forcing for high-altitude operations (the *literature ERF/ CO_2 -only ratio*), with supersonic cruise likely toward the upper end of that range: chemistry-climate assessments of proposed supersonic fleets found that the resulting stratospheric ozone and water-vapor perturbations likely contribute more to climate forcing than the fleet's CO_2 emissions [13,38], and water vapor released into the dry stratosphere can exert a larger radiative forcing per unit emission than at subsonic cruise altitudes [12]. The $2.30\times$ CO_2 penalty should therefore be interpreted as a lower bound on total climate impact. To illustrate the likely *direction and scale* of this omission—and to state its scope explicitly—we applied the upper part of the literature band, a $2.5\text{--}3\times$ *applied ERF multiplier*, to the conservative supersonic intensity alone, giving an effective $\sim 3.1\text{--}3.8$ kg CO_2e /ton-km. Set against the subsonic CO_2 -only benchmark this *asymmetric comparison ratio* was about $5.7\text{--}7\times$. We emphasize that this figure is not a like-for-like climate comparison and should not be quoted as one: it deliberately omits the subsonic fleet's own non- CO_2 forcing and serves only to bound the scale of the forcing omitted from the mass-emissions results. On a common ERF basis—the only like-for-like comparison—the multiple falls back toward the $\sim 2\text{--}3\times$ range already seen for mass CO_2 , because applying a comparable ERF multiplier to both modes leaves their ratio close to the mass- CO_2 one. The robust conclusion is therefore directional, not the precise multiple: counting non- CO_2 forcing widens the supersonic disadvantage rather than narrowing it, because supersonic cruise sits at the upper end of the ERF range through stratospheric water vapor and NO_x -ozone chemistry. Quantifying that upper-end magnitude requires a supersonic-specific ERF multiplier; the ERF-coupled climate modeling identified as future work is intended to supply it.

On the economic front, a DOC premium of \$1710 per ton and a break-even value-of-time (VOT) near \$1744/ton-hour place supersonic cargo, on these screening-level es-

timates, well outside standard logistics valuation models. That threshold is roughly $3\times$ the pharma/cold-chain ceiling (\$600/ton-hour) and $6\times$ the express/e-commerce ceiling (\$300/ton-hour) (Table 12; Figure 4), so, within the modeled assumptions and these illustrative VOT ranges, a broad commercial market appears unlikely on these figures; any adoption would have to be justified by non-priced intangibles (brand and prestige), emergencies, or bespoke premium contracts that cover the \$1144/ton-hour gap above the pharma/cold-chain ceiling. Load-factor uncertainty widens cost intensities to roughly \$2.5–3.5/ton-km (supersonic) versus \$1.2–1.7/ton-km (subsonic). Regulatory factors (sonic-boom corridors, overland restrictions) and insurance premiums, not quantified here, would further erode competitiveness. Even generous improvements in capital and maintenance assumptions cut the DOC by at most $\sim 28\%$, and lower utilization cases inflate capital burden; detailed sensitivities are reported in Sections 2.5 and 3.3.

Table 13 consolidates the CO₂ and DOC ratios reported across the paper, clarifying which assumption each line reflects. The headline conservative case was $2.30\times$ subsonic in CO₂ and $2.21\times$ in the DOC; the Monte Carlo interval kept CO₂ above parity ($1.23\text{--}1.87\times$) and the scenario envelope reached $2.64\times$ only at the most pessimistic aerodynamic/propulsion corner. The indicative DOC ratios for the baseline-aero, optimistic, and Monte Carlo cases (the square-bracketed entries in Table 13) sat in a comparatively narrow band ($\approx 2.0\text{--}2.2\times$) because the common fuel-price and load-factor draws shifted both modes together; only the conservative-cargo entry ($2.21\times$) was computed directly from a parameterized DOC re-run.

Table 12. Illustrative Freight value-of-time (VOT) ranges (author estimates).

Cargo Type	VOT Range (\$/ton-hour)	Source
Express/e-commerce	100–300	Author estimate
Pharmaceuticals (cold-chain)	300–600	Author estimate
High-value electronics	150–400	Author estimate, informed by [4]
Bulk/low value	10–50	Author estimate

Notes: Ranges are order-of-magnitude indications synthesized by the authors for screening purposes rather than values reported in a published source. The ad valorem time-cost equivalents of Hummels and Schaur [4] inform the discussion but are not tabulated here, as they are expressed as percent-of-shipment-value per day rather than \$/ton-hour.

From a policy perspective, adding carbon pricing would widen the DOC gap modestly but predictably. At \$100 per ton CO₂ ($=\$0.10/\text{kg}$), the conservative supersonic intensity (1.25 kg/ton-km) would incur $\sim \$0.13/\text{ton-km}$, versus $\sim \$0.055/\text{ton-km}$ for subsonic (0.545 kg/ton-km), increasing the DOC difference by $\sim \$0.07/\text{ton-km}$ (about \$105 per ton over 1500 km). This reinforces that environmental policy instruments further disadvantage supersonic cargo relative to incumbent air freight.

The VOT ranges in Table 12 are illustrative and deliberately heterogeneous. They are the authors' order-of-magnitude screening estimates, informed by the ad valorem time-cost equivalents (percent of shipment value per day) estimated from trade flows [4], and they vary with commodity value, lane, urgency, and geographic scope. We therefore treat them as an order-of-magnitude band rather than a single threshold. Figure 4 makes the comparison explicit: the break-even VOT generally decreased with stage length as the time saving grew, although for the conservative configuration it turned sharply upward at long range as block fuel escalated with the gross-weight build-up, terminating at the *weight-limited maximum range*—the stage length beyond which the Breguet fuel fraction can no longer close the weight budget for that low-L/D, high-SFC design. Across all the feasible distances examined (up to each scenario's weight-limited maximum range) the break-even VOT nonetheless stayed above even the pharma/cold-chain ceiling (\$600/ton-hour), so the qualitative conclusion does not hinge on any single VOT estimate.

Value-of-Time Break-Even: Supersonic vs Subsonic Cargo

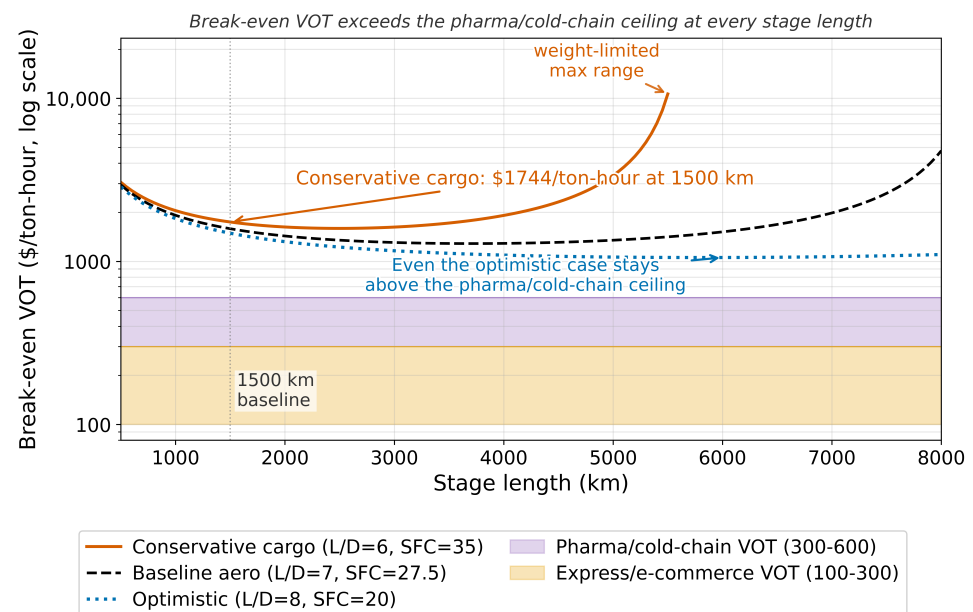


Figure 4. Value-of-time break-even (VOT, \$/ton-hour) as a function of stage length for three supersonic scenarios: conservative cargo (L/D = 6, SFC = 35), baseline aero (L/D = 7, SFC = 27.5), and optimistic (L/D = 8, SFC = 20). Shaded bands indicate the illustrative VOT ranges of Table 12 for pharma/cold-chain (\$300–600/ton-hour) and express/e-commerce (\$100–300/ton-hour). The break-even VOT generally decreases with stage length as the time saving grows—turning upward for the conservative scenario near its weight-limited maximum range (annotated), where the Breguet fuel fraction can no longer close the weight budget—but remains well above these illustrative VOT ranges over all feasible distances (up to each scenario’s weight-limited maximum range).

Table 13. Consolidated CO₂ and DOC ratios relative to the subsonic benchmark (1500 km, 1-ton functional unit).

Case	CO ₂ (kg/ton-km)	CO ₂ Ratio	DOC Ratio [†]
<i>Directly computed (parameterized DOC re-run):</i>			
Subsonic benchmark	0.545	1.00×	1.00×
Conservative cargo (headline)	1.25	2.30×	2.21×
<i>CO₂ directly computed; DOC indicative (evaluated at baseline cost inputs, not independently re-computed):</i>			
Baseline aero (M = 1.8, L/D = 7.0, SFC = 27.5)	0.85	1.55×	[≈2.1×
Optimistic (L/D = 8.0, SFC = 20)	0.59	1.09×	[≈2.0×
Monte Carlo 90% interval	0.67–1.02	1.23–1.87×	[≈2.0–2.2×
Scenario envelope (grid min–max)	0.52–1.44	0.96–2.64×	—

Notes: CO₂ ratios are relative to the subsonic block intensity (0.545 kg/ton-km); DOC ratios are relative to the subsonic DOC (\$0.94/ton-km). The conservative cargo case underpins the abstract and conclusion. [†] Only the conservative-cargo DOC ratio (2.21×, in bold, no brackets) is computed directly; the baseline-aero, optimistic, and Monte Carlo DOC ratios are indicative and are set apart by italic square brackets and an ≈ prefix, e.g., [≈2.1×]. These indicative ratios are evaluated at the baseline cost inputs because the DOC model is parameterized on the conservative-cargo configuration, and should be read as approximate rather than as independently computed values. The Monte Carlo median (50th percentile) CO₂ intensity is 0.82 kg/ton-km, i.e., 1.50× subsonic. The envelope row is defined for CO₂ only.

Technological advances remain the clearest lever. The supersonic grid highlights propulsion SFC and aerodynamic efficiency as the dominant drivers; investments in variable-cycle engines [8], laminar-flow control and low-drag area-ruled configurations (natural laminar flow cannot be maintained across the Mach 1.6–2.2 cruise band), and

lightweight structures could roughly halve the emissions intensity—spanning the modeled range from the conservative cargo case (1.25 kg/ton-km) to the optimistic technology corner (0.59 kg/ton-km). Conversely, at the worst aerodynamic/propulsion corner of the modeled grid ($L/D = 6.0$, $SFC = 35 \text{ mg}/(\text{N}\cdot\text{s})$, $\text{Mach} = 1.6$), CO_2 intensity reaches 1.44 kg/ton-km even before non- CO_2 effects are counted. The Mach corner here is the *lowest* value in the grid, not the highest, because the Breguet exponent carries cruise velocity in the denominator: at fixed L/D and SFC , lower Mach lengthens the time over which fuel is burned and so raises fuel fraction; this is consistent with the earlier statement (Section 3.2) that the most favorable corner combines high Mach with high L/D and low SFC . Design compromises (e.g., cargo volume, thermal limits) that pushed L/D or SFC outside these grid bounds would worsen the penalty further but lie beyond the parameter space evaluated here. Regulatory progress on low-boom operation will determine whether viable routes exist beyond transoceanic corridors [9,39]. Early supersonic operations could also see lower utilization ($\sim 1800 \text{ h/year}$ versus 3500 h/year assumed), which would raise the capital/reserve line and total DOC as quantified in Section 2.5; this sits within the DOC sensitivity band reported in the Results.

Airframe configuration offers a further lever for future cargo aircraft, and the blended wing body (BWB) is among the most extensively studied departures from the conventional tube-and-wing layout. Conceptual passenger-transport studies report double-digit reductions in fuel burn per seat-mile relative to technology-matched conventional baselines [40,41]; these gains should not, however, be read directly as reductions per cargo ton-km. Freight nevertheless remains an attractive application: the passenger-specific constraints associated with a windowless cabin, passenger acceptance, and emergency egress [41] are substantially less restrictive for a freighter, and the wide centerbody offers substantial payload volume, although the non-cylindrical pressure vessel remains a structural challenge for a pressurized cargo bay, and dedicated cargo-derivative studies of the closely related hybrid wing body indicate that loading arrangements and unit-load-device geometry must be tailored specifically to the blended planform [42]. For the comparison performed here, a mature BWB freighter could reduce the fuel-use and direct CO_2 -emission intensity of the subsonic benchmark, potentially widening the supersonic penalties reported above; its effect on total cost intensity is less certain, as acquisition, certification, maintenance, and airport-compatibility effects would require a dedicated economic assessment. The BWB concepts behind the cited performance figures are subsonic–transonic transports, and their performance does not transfer directly to low-boom supersonic configurations, which must be optimized separately for wave drag and sonic-boom shaping. A quantitative BWB-freighter benchmark is therefore a natural extension of this cross-modal framework when sufficiently mature design data become available.

Future research will focus on (i) coupling the emissions and DOC model with ERF-based climate metrics [43], (ii) extending the mission library to full network simulations with stochastic demand, (iii) incorporating noise and materials fatigue constraints, and (iv) validating emission indices for supersonic propulsion through engine test-cell data. The code and data in the accompanying public repository (see Data Availability) enable reproducibility and facilitate peer benchmarking against emerging supersonic concepts.

5. Conclusions

By recalculating emissions from combustion physics and decomposing direct operating costs, this study clarifies the trade space for supersonic cargo transport and answers the two research questions posed in the Introduction: at the 1500 km baseline, first-generation supersonic cargo carries CO_2 and DOC penalties of $2.30\times$ and $2.21\times$ relative to advanced subsonic freight (RQ1), and the implied break-even value of time is roughly $3\text{--}6\times$ the upper illustrative willingness-to-pay benchmarks (RQ2). These headline multiples are

scenario-conditional: they quantify the modeled first-generation assumptions about engine SFC, payload, and operating model, and the reported scenario envelope and Monte Carlo intervals bound how far plausible changes in those assumptions move them; the modal ranking, not the exact multiples, is the robust result. We separate the conclusions into those that are robust to technology improvement and those that are conditional on policy and market structure; all are conditional on the screening-level assumptions of Section 2, and the market-oriented statements additionally on the illustrative value-of-time ranges in Table 12.

Technical thresholds for competitiveness. Even under conservative assumptions, first-generation supersonic cargo delivers $2.30\times$ the CO₂ intensity of subsonic freighters; this conservative point sits above the Monte Carlo median (closer to $1.50\times$, with a 90% interval of $1.23\text{--}1.87\times$) but within the scenario envelope, which reaches $2.64\times$ under pessimistic parameter combinations. Short stage lengths amplify the penalty through fixed mission overheads. SFC is the controlling parameter ($\pm 40\%$), so approaching subsonic intensity requires propulsion efficiency gains (toward the low end of the 20–35 mg/(N·s) band) combined with high cruise L/D (≈ 8); aerodynamic or Mach gains alone are insufficient. These targets are technology prerequisites, independent of cost.

Policy and market implications. The DOCs remain $2.21\times$ the subsonic DOC—taken in isolation an upper-leaning estimate, because whole-aircraft crew and fees and the small-payload capital and maintenance rates are charged in full to the single costed ton (Section 2.5)—implying a break-even willingness to pay of roughly \$1744/ton-hour saved—about $3\times$ the \$600/ton-hour upper bound of the pharma/cold-chain range and $6\times$ the \$300/ton-hour upper bound of the express range in Table 12, and therefore likely beyond conventional willingness-to-pay on these illustrative benchmarks, absent non-priced intangibles or emergency use. Carbon pricing widens the gap by a small but foreseeable margin, and unmodeled regulatory and insurance costs would widen it further; conversely, low-boom routing progress is what determines whether viable lanes exist at all. On this screening-level evidence, supersonic cargo is therefore best understood as a specialized, time-critical niche pending both propulsion advances and a favorable regulatory regime.

Limitations. These conclusions inherit the screening-level scope cataloged in Section 2.7: mission performance uses a steady-cruise Breguet formulation, DOC inputs are stylized rather than drawn from operator ledgers, and the quantitative climate metrics count mass emissions only, with non-CO₂ forcing (NO_x–ozone chemistry, stratospheric water vapor, and contrails) entering only as an illustrative bound in the Discussion. Constant emission indices likely narrow the NO_x upper bound, and the 5–10-ton payload assumption presumes the volumetric bay can be filled. Because the dominant biases—climate metrics, DOC scope, and utilization—all act to understate the supersonic penalty (the bias directions itemized in Section 2.7; the non-CO₂ forcing bound is quantified in Section 4 [12,36]), the headline $2.30\times$ and $2.21\times$ ratios should be read as conservative bounds; the results are intended to rank concepts and bound penalties, not to size fleets or certify designs. Future work will extend the model with effective radiative forcing metrics and stochastic network simulations, building on the code and data that accompany this submission for reproducible assessment of emerging supersonic concepts.

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Abbreviations

The following abbreviations are used in this manuscript:

CO ₂	carbon dioxide
CO ₂ e	carbon dioxide equivalent
NO _x	nitrogen oxides
H ₂ O	water (vapor)
DOC	direct operating cost
EF	emission factor (mass per ton-km)
EI	emission index (mass per kg fuel)
ERF	effective radiative forcing
VOT	value of time
SFC	specific fuel consumption (thrust-specific)
L/D	lift-to-drag ratio
SST	supersonic transport
SBJ	supersonic business jet
SAF	sustainable aviation fuel
LCA	life-cycle assessment
OPR	overall pressure ratio
OEW	operating empty weight
MTOW	maximum take-off weight
LTO	landing–take-off (cycle)
CCD	climb/cruise/descent (mission segments)
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
EIA	U.S. Energy Information Administration
CPI-U	Consumer Price Index for All Urban Consumers

Appendix A. Data Underlying the Fixed-Overhead Cross-Check

Table A1 reproduces the per-type fuel-burn data behind the 112–140 kg CO₂ per design-payload-ton bracket of Section 2.3. The landing–take-off (LTO) cycle and climb/cruise/descent (CCD) fuel values are transcribed from the Annex 1 “master emissions calculator” (v1.5, 18 September 2024; year-2022 fleet-average estimations, © EUROCONTROL) of the aviation chapter (1.A.3.a) of the EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023 [22]; the calculator tabulates fuel burn for the corresponding passenger variants (calculator identifiers B77L-A, B763-A, and B744-A) at fixed great-circle mission distances, of which the five used here span 125–750 nautical miles (232–1389 km). For each type, block fuel (LTO plus CCD) is regressed on great-circle stage length by ordinary least squares; the intercept is the implied fixed (non-cruise) fuel burn, which is converted at the manuscript’s 3.16 kg CO₂/kg fuel convention (the calculator’s native factor

is 3.15) and divided by the corresponding freighter variant's published design payload to yield the implied fixed overhead per design-payload ton quoted in Section 2.3.

Table A1. Per-type block-fuel data and fitted fixed fuel burns underlying the overhead cross-check.

Quantity	B777F-Class (B77L-A)	B767-300F-Class (B763-A)	B747-400F-Class (B744-A)
LTO fuel (kg)	2906.8	1729.9	3908.4
CCD fuel, 125 nmi/232 km (kg)	2731.7	1821.0	3368.6
CCD fuel, 200 nmi/370 km (kg)	3997.8	2634.8	4958.9
CCD fuel, 250 nmi/463 km (kg)	4958.3	3084.6	5936.4
CCD fuel, 500 nmi/926 km (kg)	8606.0	5547.7	10,582.8
CCD fuel, 750 nmi/1389 km (kg)	12,623.6	8137.1	15,328.3
Fitted fixed (non-cruise) fuel (kg)	3782	2311	5015
Regression R^2	0.9993	0.9998	0.9998
Freighter design payload (t)	107	57	113
Implied fixed overhead (kg CO ₂ /ton)	112	128	140

Notes: Block fuel = LTO + CCD fuel at each tabulated great-circle distance [22]. The fitted fixed fuel is the intercept of the ordinary-least-squares fit of block fuel on stage length over 232–1389 km; the implied overhead equals that intercept multiplied by 3.16 kg CO₂/kg fuel and divided by the freighter variant's design payload. Because the underlying fuel data are fleet averages for the corresponding passenger variants, the implied overheads are indicative rather than exact (Section 2.3). The regression is reproduced by the accompanying code repository (see Data Availability).

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