

The Global Aviation Industry Ecosystem

A Country-Level and Industry-Level Quantitative Framework for Airports, Airlines, Cargo, Aviation Businesses, Economic Contribution, Resilience and Sustainable Growth

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Abstract

This study develops a multilevel framework for analysing the global aviation industry as an integrated ecosystem of airports, airlines, air cargo, aircraft fleets, aviation businesses, employment, tourism, trade and economic contribution. The paper addresses a recurring measurement problem in aviation research: airport passenger journeys, country passenger markets, airline passengers and revenue passenger kilometres are related but non-equivalent measures. A source-harmonized architecture is therefore proposed using Airports Council International (ACI), International Air Transport Association (IATA), Air Transport Action Group (ATAG), ICAO/World Bank and national aviation sources. Verified benchmarks show that ACI's final 2025 dataset covered 2,817 airports across more than 180 countries and territories and recorded 9.8 billion airport passenger journeys. IATA's 2025 World Air Transport Statistics incorporates 1,315 airlines; the United States and China were the two largest country passenger markets, with 890.1 million and 776.1 million passengers respectively. ATAG estimates that aviation supported 86.5 million jobs and US\$4.1 trillion of global economic activity in 2023, while 4,072 airports had scheduled commercial flights. The study proposes three complementary constructs: a Global Aviation Development Index (GADI), an Aviation Business Ecosystem Index (ABEI), and an Airport Ecosystem Intensity index (AEI). It further specifies country fixed-effects panel models for passenger demand, cargo activity and economic contribution over 2015–2025, with 2026 treated separately as a current-market layer. The framework is designed to support reproducible cross-country research without conflating historical observations, current monthly indicators and forecasts.

Keywords: global aviation industry; airports; airlines; air cargo; aviation economics; connectivity; aviation development index; airport infrastructure; tourism; trade; panel data; sustainable aviation

1. Introduction

Air transport is simultaneously a transport network, infrastructure system, service industry, manufacturing ecosystem and facilitator of international trade and tourism. Its economic relevance extends beyond airline revenue because airports, air navigation services, aerospace manufacturing,

maintenance, leasing, ground handling, logistics, travel services and aviation-enabled tourism form interdependent value chains.

The global scale is substantial. ACI's final 2025 airport dataset recorded 9.8 billion passenger journeys at 2,817 airports across more than 180 countries and territories, with traffic 3.7% above 2024 and 6.5% above 2019. ATAG's 2023 structural baseline identifies 4,072 airports with scheduled commercial flights, 1,138 airlines, 29,039 commercial aircraft and 67,300 routes. These figures are not contradictory: they use different concepts and reporting universes. A central contribution of this study is to preserve those distinctions rather than collapse them into a single 'number of airports' or 'number of passengers'.

The paper also responds to a second limitation in broad aviation studies: national aviation development is often proxied by passenger traffic alone. Yet passenger volume does not reveal whether a country has a diversified aviation business ecosystem, strong cargo activity, high airport utilization, deep international connectivity, domestic aerospace manufacturing or substantial aviation employment. The proposed framework therefore treats aviation development as multidimensional.

The research has four objectives: (1) document the scale and structure of the global aviation ecosystem; (2) develop a reproducible country-level data architecture; (3) propose multidimensional measures of aviation development, business depth and airport intensity; and (4) specify econometric models capable of testing relationships among aviation, GDP, trade, tourism and employment.

2. Research Questions and Hypotheses

RQ1. How are airports, airline passenger markets, cargo activity and aviation businesses distributed across countries and regions?

RQ2. Which economic and infrastructure variables are associated with national passenger and cargo activity?

RQ3. How are connectivity, tourism and trade associated with aviation-system development?

RQ4. How did the COVID-19 shock and subsequent recovery alter cross-country aviation patterns?

RQ5. How do mature, emerging, hub-oriented, tourism-oriented and cargo-oriented aviation systems differ?

RQ6. Can a multidimensional Global Aviation Development Index provide a useful synthesis of national aviation ecosystems?

RQ7. What structural forces are likely to shape aviation through 2030–2045?

The testable hypotheses are: H1 airport infrastructure is positively associated with passenger activity; H2 GDP per capita is positively associated with passenger demand per capita; H3 international connectivity is positively associated with international passenger activity; H4 tourism is positively associated with international aviation activity; H5 trade is positively associated with air-cargo activity; H6 aviation-business ecosystem depth is positively associated with national aviation development; H7 aviation development is positively associated with aviation-supported employment and economic contribution; H8 passenger load factor is positively associated with airline operating performance after controlling for costs and demand; H9 fuel-cost increases are negatively associated with airline financial performance; H10 major external disruptions are associated with lower affected traffic; H11

aviation-development relationships differ across regions; and H12 determinants differ between mature and emerging markets.

3. Literature Review and Theoretical Background

3.1 Aviation and economic growth

The aviation–growth relationship is theoretically bidirectional. Higher income, industrial production and trade increase demand for air travel and freight; simultaneously, connectivity can reduce generalized transport costs, expand market access, support tourism, enable high-value trade and improve access to human capital. Empirical studies have reported heterogeneous causal patterns across regions and development levels, which supports the use of country and time effects rather than a single universal cross-sectional relationship.

3.2 Airports as economic and network infrastructure

Airports perform multiple functions: local infrastructure, national gateways, transfer hubs, cargo nodes and commercial real-estate platforms. Airport count alone is therefore an incomplete measure. Utilization, internationalization, cargo intensity, movements and connectivity are required to distinguish infrastructure availability from infrastructure productivity.

3.3 Cargo, trade and high-value supply chains

Air cargo has an economic profile different from passenger aviation. ATAG reports that air transport carries less than 1% of world trade shipments by volume but around 33% by value. This concentration in high-value and time-sensitive commodities makes cargo tonne-kilometres and cargo value conceptually distinct from passenger measures.

3.4 Tourism and employment channels

Aviation-enabled tourism is a major component of the sector's wider economic footprint. ATAG estimates 37.3 million aviation-enabled tourism jobs within 86.5 million total aviation-supported jobs in 2023. This motivates explicit tourism variables rather than treating tourism as a peripheral control.

3.5 Sustainability and technological transition

The sector faces a long-run decarbonization constraint. ATAG reports 882 million tonnes of aviation CO₂ in 2023 and a sector goal of net-zero carbon emissions by 2050. Sustainable aviation fuel, fleet renewal, operational efficiency and infrastructure improvements are central transition mechanisms. ATAG reports more than 140 SAF projects underway as of 2025 and 170+ airports distributing SAF.

4. Global Aviation Industry Structure

Indicator	Value	Reference year
Airport passenger journeys	9.8 billion	2025
Airports in ACI final traffic dataset	2,817	2025
ACI country/territory coverage	180+	2025
Scheduled commercial airports	4,072	2023

Airlines	1,138	2023
Commercial aircraft in service	29,039	2023
Routes	67,300	2023
Scheduled commercial flights	35.3 million	2023
Airline passengers carried	4.4 billion	2023
Revenue passenger kilometres	8.17 trillion	2023
Air cargo	61.4 million tonnes	2023
Direct aviation jobs	11.6 million	2023
Total aviation-supported jobs	86.5 million	2023
Direct aviation GDP	US\$1.1 trillion	2023
Total economic contribution	US\$4.1 trillion	2023
Global GDP supported	3.9%	2023

Table 1 deliberately retains different reference years. The 2025 ACI observations describe airport traffic, whereas ATAG's structural and economic baseline is principally for 2023. Combining them without year labels would create a false single-year dataset.

4.1 Largest country passenger markets in 2025

Rank	Country	Passengers	YoY change
1	United States	890.1m	+1.6%
2	China	776.1m	+4.8%
3	United Kingdom	269.7m	+3.4%
4	Spain	252.7m	+5.0%
5	Japan	223.5m	+9.2%
6	India	218.2m	+3.3%
7	Italy	187.3m	+5.8%
8	Germany	163.8m	+3.4%
9	France	152.6m	+2.2%
10	Türkiye	129.3m	+2.9%

IATA defines these as scheduled passengers originating or terminating in each country. Domestic journeys are counted once, while international journeys are counted in both origin and destination countries. Consequently, this variable should not be substituted for ACI airport passenger throughput.

Market size and market growth are also different dimensions. Kazakhstan reached 18.1 million passengers in 2025 with 40.0% year-on-year growth, Uzbekistan 12.5 million with 16.9% growth, and Vietnam 80.9 million with 14.8% growth. Such markets may have smaller absolute scale but faster expansion than mature aviation systems.

4.2 Fleet utilization and technological change

Aircraft family/type	Flights in 2025	Change vs 2019
Boeing 737	10.8m	+3.1%
Airbus A320	8.7m	+7.6%

Airbus A321	4.2m	+61.6%
Embraer E170/E190	2.7m	+2.8%
Airbus A319	1.4m	-34.3%
Boeing 787	795k	+40.8%
Airbus A220	530k	+770.4%
Airbus A350	434k	+117.4%
Airbus A380	90k	-24.4%

The 2025 flight counts show a marked shift toward newer narrowbody and widebody types, although flight-count growth should not be interpreted as a direct fleet-size measure.

5. Measurement Framework

5.1 Passenger concepts

Four passenger concepts must remain separate: airport passenger journeys, country passenger markets, airline passengers carried, and revenue passenger kilometres (RPK). RPK measures transport work rather than headcount. Formally, RPK is the sum of revenue passengers multiplied by distance flown. Available seat kilometres (ASK) measure capacity, and passenger load factor (PLF) is RPK divided by ASK.

5.2 Airport concepts

The study distinguishes all aerodromes, airports with scheduled commercial service, airports reporting to a given traffic database, and major commercial airports above defined thresholds. The ACI figure of 2,817 refers to airports represented in its final 2025 traffic dataset; ATAG's 4,072 figure refers to airports with scheduled commercial flights.

5.3 Core transformations

To reduce scale effects, selected variables will be analysed in natural logarithms. Per-capita indicators will include passengers per capita, cargo per capita, airports per million residents and fleet per million residents. Economic-intensity indicators will include aviation GDP share, trade intensity and tourism intensity. Airport productivity indicators will include passengers per commercial airport, cargo per commercial airport and movements per commercial airport.

6. Proposed Composite Indices

6.1 Global Aviation Development Index (GADI)

GADI is defined as a hierarchical construct combining airport infrastructure, passenger activity, cargo activity, connectivity, fleet/capacity, business ecosystem, employment and economic contribution. Standardized variables will be screened using correlation diagnostics, KMO and Bartlett tests before principal component analysis. PCA-derived weights will be compared with an equal-weight robustness specification. The index may be rescaled to 0–100 for communication, but the paper will emphasize structural profiles and clusters rather than a simplistic league table.

Conceptually: $GADI_i = \sum w_j Z_{ij}$, where $\sum w_j = 1$ and Z_{ij} is the standardized value of component j for country i .

6.2 Aviation Business Ecosystem Index (ABEI)

ABEI captures the depth and diversity of airlines, airport operators, aerospace manufacturing, engines/components, MRO, leasing/finance, cargo/logistics and aviation technology. Where reliable data permit, employment or revenue weights will be preferred to simple company counts.

6.3 Airport Ecosystem Intensity (AEI)

AEI distinguishes airport availability from airport utilization. Candidate indicators are passengers per airport, cargo per airport, movements per airport and connectivity. This is important because countries with numerous lightly used airports are structurally different from hub economies with a small number of intensely utilized airports.

7. Data and Methodology

7.1 Study periods and samples

The main annual panel is designed for 2015–2025. Four analytical periods are distinguished: 2015–2019 pre-pandemic baseline; 2020–2022 disruption and early recovery; 2023–2025 normalization; and 2026 as a separate current-year layer using monthly realized observations and clearly identified forecasts. Long-term 2030–2045 values are treated only as scenarios or external forecasts.

The descriptive database is intended to cover approximately 190+ economies where reliable observations exist. The principal econometric sample will include only countries meeting a pre-specified data-completeness threshold, provisionally 80% of required country-year observations. The final N must be reported after data assembly.

7.2 Data-quality hierarchy

Observations will be coded A for directly observed official/primary data, B for calculations from official data, C for authoritative secondary estimates, D for statistically imputed values and NA for unavailable observations. Principal models should initially use A–C observations; imputed values can be introduced in sensitivity analysis.

7.3 Panel models

Passenger model: $\ln(PASS_{it}) = \beta_0 + \beta_1 \ln(GDPPC_{it}) + \beta_2 \ln(POP_{it}) + \beta_3 \ln(AIRPORTS_{it}) + \beta_4 TOURISM_{it} + \beta_5 TRADE_{it} + \beta_6 CONNECTIVITY_{it} + \mu_i + \lambda_t + \varepsilon_{it}$.

Cargo model: $\ln(CARGO_{it}) = \alpha_0 + \alpha_1 TRADE_{it} + \alpha_2 \ln(GDP_{it}) + \alpha_3 CONNECTIVITY_{it} + \alpha_4 AIRPORTS_{it} + \alpha_5 INDUSTRY_{it} + \mu_i + \lambda_t + \varepsilon_{it}$.

Economic contribution model: $\ln(AVGDP_{it}) = \delta_0 + \delta_1 GADI_{it} + \delta_2 \ln(GDP_{it}) + \delta_3 TOURISM_{it} + \delta_4 TRADE_{it} + \mu_i + \lambda_t + \varepsilon_{it}$.

Model selection will compare pooled OLS, country fixed effects and random effects, followed by Hausman testing where appropriate. Robust or country-clustered standard errors will be used where diagnostics indicate heteroskedasticity or within-country dependence.

7.4 Structural break and recovery

COVID-period indicators will identify the disruption phase. A recovery index can be calculated as $\text{Traffic}_{2025} / \text{Traffic}_{2019} \times 100$, where 100 indicates recovery to the 2019 level. A CAGR-based measure provides a standardized longer-run comparison.

7.5 Cluster analysis

Hierarchical clustering followed by k-means refinement can identify empirically distinct aviation-system types. Candidate labels such as mature hub, emerging growth, tourism-oriented and cargo-oriented will be assigned only after examining cluster centroids; labels will not be imposed ex ante.

8. Verified Descriptive Findings

8.1 Airport recovery and concentration

ACI reports that global airport passenger traffic reached 9.8 billion in 2025, 6.5% above 2019. The top 20 airports handled 1.59 billion passengers. Using the published totals, $\text{CR}_{20} = 1.59 / 9.8 \times 100 \approx 16.2\%$. Thus, approximately one-sixth of global airport passenger journeys were concentrated in only 20 airports, while the majority of traffic remained distributed across a long tail of airports.

8.2 Employment and economic contribution

ATAG estimates 11.6 million direct aviation jobs, 20.4 million indirect jobs, 17.2 million induced jobs and 37.3 million aviation-enabled tourism jobs in 2023, totaling 86.5 million supported jobs. Aviation-enabled tourism therefore represented approximately 43.1% of the total supported-employment estimate. ATAG also estimates US\$1.1 trillion in direct aviation GDP and US\$4.1 trillion in total economic contribution, equivalent to 3.9% of global GDP.

8.3 Trade facilitation

ATAG reports that air transport represents around 33% of world trade by value while carrying less than 1% by volume. This highlights the disproportionate role of aviation in high-value, time-sensitive and perishable supply chains.

8.4 Sustainability transition

ATAG reports 882 million tonnes of aviation CO₂ emissions in 2023. The organization also reports that 1 million tonnes of SAF were used for commercial flights in 2024, with 2025 production estimated at 2.1 million tonnes, or 0.7% of airline fuel consumption. These figures indicate that SAF deployment is expanding from a small base and remains far below the scale implied by long-run net-zero pathways.

9. Current 2026 Industry Conditions

IATA's June 2026 Global Outlook describes a severe energy and refinery shock affecting airline economics, including sharply higher jet-fuel costs and disrupted supply chains. Because this report contains full-year outlook values, those observations should be treated as forecasts rather than realized annual results.

The current-year layer should be kept analytically separate from the completed 2015–2025 annual panel. Monthly 2026 observations are useful for shock and resilience analysis, but they should not be substituted for full-year country observations.

10. Discussion

The descriptive evidence supports a central proposition: global aviation is too heterogeneous to be represented by one traffic variable. The United States and China dominate country passenger-market scale, while smaller Central Asian and Southeast Asian markets can exhibit much faster growth. Airport leadership also depends on the chosen metric: total passengers, international passengers, cargo and aircraft movements identify different operational leaders. At the macroeconomic level, the large employment and GDP estimates arise from direct aviation activity plus supply-chain, induced and tourism channels, and these components should not be interpreted as equivalent.

The distinction between infrastructure stock and infrastructure intensity is equally important. A high airport count may reflect geography, public-service requirements or dispersed settlement rather than high commercial throughput. Conversely, hub economies may operate a small number of airports at extremely high intensity. The AEI is designed to capture this difference.

The proposed business ecosystem dimension also broadens conventional country comparisons. Passenger traffic can be large even where aircraft manufacturing, leasing, MRO and aviation technology remain limited. Conversely, some economies may exert global influence through aerospace production or leasing despite modest domestic passenger populations. ABEI therefore complements traffic-based measures.

11. Managerial and Policy Implications

For airport authorities, the framework encourages benchmarking on utilization, connectivity and cargo specialization rather than airport count alone. For airlines, it highlights the joint importance of demand, capacity, load factor, fuel costs and network resilience. For national policymakers, it separates aviation consumption from aviation industrial capability: policies designed to expand passenger access are not identical to policies designed to build MRO, manufacturing, leasing or logistics clusters.

For emerging markets, rapid traffic growth creates infrastructure and capacity opportunities but also raises questions about congestion, workforce availability, financing and environmental performance. For mature markets, growth may depend more heavily on productivity, fleet modernization, airport capacity management and decarbonization than on simple network expansion.

12. Sustainability, Technology and the 2030–2045 Outlook

Long-run aviation development will be shaped by fleet replacement, sustainable aviation fuel, digital operations, AI-supported planning, airport automation, airspace modernization and supply-chain resilience. ATAG forecasts aviation's total economic contribution could reach US\$8.5 trillion by 2043, but such long-range values are scenario-dependent and should not be presented as observed outcomes.

The paper proposes three scenario families for subsequent quantitative work: a baseline growth scenario, a constrained-growth scenario incorporating infrastructure, energy and geopolitical

limitations, and a sustainability-transition scenario incorporating faster fleet renewal and SAF deployment. Scenario outputs should remain separate from historical regressions.

13. Limitations

First, global aviation databases use different definitions, reporting universes and publication lags. Second, country-level aviation economic-impact estimates are not uniformly available. Third, cross-country company counts can be misleading unless business size is considered. Fourth, aviation and economic growth may be jointly determined, creating endogeneity concerns that fixed effects alone cannot fully resolve. Fifth, current-year 2026 monthly observations are incomplete and cannot be treated as full-year results. Finally, the GADI, ABEI and AEI require empirical validation before substantive country comparisons are reported.

14. Conclusion

This study establishes a reproducible framework for analysing the global aviation industry across infrastructure, passenger demand, cargo, connectivity, fleet activity, business ecosystems, employment and economic contribution. Verified industry data show the exceptional scale of aviation: 9.8 billion airport passenger journeys in ACI's 2025 dataset, 1,315 airlines represented in IATA's WATS collection, and an ATAG-estimated 86.5 million aviation-supported jobs and US\$4.1 trillion economic contribution in 2023. Yet these headline values also demonstrate the importance of measurement discipline because they refer to different units, years and statistical universes.

The principal academic contribution is therefore methodological as well as substantive. Rather than treating airport count or passenger volume as a complete proxy for aviation development, the proposed GADI, ABEI and AEI framework captures multiple dimensions of national aviation systems. The next empirical phase is to populate the harmonized 2015–2025 country panel, estimate PCA weights and clusters, and test the specified panel models. Until that phase is completed, this manuscript reports verified descriptive findings and transparent model specifications rather than invented inferential statistics.

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Appendix A. Proposed Country-Year Data Dictionary

Code	Definition	Unit	Preferred source
COUNTRY	Country/economy	Text	ISO/national
YEAR	Observation year	Year	All
POP	Population	Persons	World Bank
GDP	Gross domestic product	US\$	World Bank
GDPPC	GDP per capita	US\$	World Bank
AIRPORTS	Scheduled commercial airports	Count	ICAO/ATAG/national
APT_PAX	Airport passenger journeys	Passengers	ACI/national
MKT_PAX	Country passenger market	Passengers	IATA
RPK	Revenue passenger	Passenger-km	IATA/ICAO

	kilometres		
ASK	Available seat kilometres	Seat-km	IATA/ICAO
PLF	Passenger load factor	%	IATA/ICAO
CARGO_T	Air cargo	Tonnes	ACI/ICAO
CTK	Cargo tonne kilometres	Tonne-km	IATA/ICAO
TOUR	Tourism activity	Arrivals/receipts	UN Tourism/WB
TRADE	International trade	US\$	WB/WTO
FLEET	Commercial aircraft	Count	ICAO/IATA/company
ROUTES	Air routes	Count	ICAO/IATA
AVEMP	Aviation-supported employment	Jobs	ATAG/national
AVGDP	Aviation-supported GDP	US\$	ATAG/national
GADI	Global Aviation Development Index	Index	Calculated
ABEI	Aviation Business Ecosystem Index	Index	Calculated
AEI	Airport Ecosystem Intensity	Index	Calculated

Appendix B. Source and Definition Rules

15. Technical and Scientific Quantitative Analysis

This section extends the descriptive manuscript with reproducible aviation-engineering, concentration, productivity, environmental-intensity and forecasting calculations. Every worked calculation below is derived from published aggregate observations and is therefore distinguishable from the proposed econometric results, which still require the harmonized country-year panel.

15.1 Airport throughput intensity

Using ACI's final 2025 total of 9.8 billion passenger journeys across 2,817 airports, the arithmetic mean throughput is: Average airport throughput = $9.8 \times 10^9 / 2,817 = 3.479$ million passenger journeys per airport. This is a system-wide arithmetic mean, not the throughput of a typical airport; the distribution is strongly right-skewed because of mega-hubs.

For the empirical dataset, median throughput, interquartile range, coefficient of variation and percentile ratios should therefore accompany the mean. A recommended dispersion statistic is $CV = \sigma/\mu \times 100$, while skewness should be reported before applying logarithmic transformations.

15.2 Airport concentration ratios

ACI reports 1.59 billion passengers at the 20 busiest airports in 2025. Hence $CR_{20} = 1.59/9.8 \times 100 = 16.22\%$. The complementary share outside the top 20 is 83.78%.

The three largest airports—Atlanta (106.3m), Dubai (95.2m) and Tokyo Haneda (91.7m)—collectively handled 293.2 million passengers. Relative to 9.8 billion global airport journeys, their approximate combined share is 2.99%.

When airport-level traffic shares become available, the Herfindahl-Hirschman Index should be calculated as $HHI = \sum s_i^2$. A normalized HHI can additionally be reported as $(HHI - 1/N)/(1 - 1/N)$, permitting comparison across samples with different numbers of airports.

15.3 Recovery and compound growth

ACI reports 2025 passenger traffic 6.5% above 2019. Treating this as a six-year endpoint comparison, the implied compound annual growth rate is $CAGR = (1.065)^{(1/6)} - 1 = 1.06\%$ per year. This is a mathematical endpoint CAGR and should not be interpreted as a smooth annual path because 2020–2022 contained an extraordinary structural break.

At country or airport level, Recovery Index = $Traffic_{2025} / Traffic_{2019} \times 100$. Values above 100 indicate traffic above the 2019 benchmark; values below 100 indicate incomplete recovery.

15.4 Passenger capacity efficiency

Passenger load factor is $PLF = RPK/ASK \times 100$. IATA reports 2025 global RPK growth of 5.3%, ASK growth of 5.2%, and PLF of 83.6%. A useful demand-capacity balance metric is $DCB = \Delta RPK - \Delta ASK$. For 2025, $DCB = 5.3 - 5.2 = +0.1$ percentage point, indicating that demand growth marginally exceeded capacity growth.

At market level, a positive DCB indicates demand expanding faster than offered capacity, while a negative value indicates capacity expanding faster than traffic. This metric should be interpreted jointly with the level and change of PLF.

15.5 Aviation employment structure and economic-impact ratios

Using ATAG's 2023 estimates, direct aviation employment represented $11.6/86.5 \times 100 = 13.41\%$ of total aviation-supported employment. Aviation-enabled tourism represented $37.3/86.5 \times 100 = 43.12\%$.

The ratio of ATAG's total supported economic contribution (US\$4.1 trillion) to direct aviation GDP (US\$1.1 trillion) is 3.73. This is an accounting ratio between two impact categories and must not be described as a causal econometric multiplier.

15.6 Carbon-intensity calculations

ATAG reports 882 million tonnes of aviation CO₂ in 2023 against approximately 43 billion tonnes of total human CO₂. The corresponding share is $882/43,000 \times 100 = 2.05\%$.

Using ATAG's 2023 RPK benchmark of 8.17 trillion solely as a broad denominator, an aggregate operational intensity calculation gives approximately 108.0 grams CO₂ per RPK. This is an aggregate ratio, not a passenger-specific life-cycle footprint: freight activity, belly cargo, aircraft operations and differences in system boundaries make direct comparison with route-level passenger carbon calculators inappropriate.

ATAG separately reports that a typical new-generation single-aisle aircraft emits around 50 g CO₂ per seat-kilometre, illustrating why seat-kilometre and revenue-passenger-kilometre intensities should not be treated as identical.

15.7 Fleet technology transition

Fleet modernization can be quantified through an Aircraft Technology Transition Ratio (ATTR): $ATTR_j = \text{Flights}_{2025,j} / \text{Flights}_{2019,j}$. For example, the Airbus A350 ratio is $434,000/200,000 = 2.17$, whereas the Airbus A380 ratio is $90,000/119,000 \approx 0.76$. The Airbus A220 ratio is approximately 8.69. These are utilization ratios based on flight counts, not fleet-stock ratios.

A broader Fleet Modernization Index could weight aircraft-family flight shares by technology generation, but such weights should be justified using fuel-burn or emissions-performance evidence rather than assigned subjectively.

15.8 Market concentration among the ten largest country passenger markets

The ten largest IATA country passenger markets listed in the 2025 WATS release sum to approximately 3263.3 million passenger-market observations. The United States and China together contribute 1666.2 million, or 51.06% of this top-ten subtotal. This is a concentration measure within the published top-ten subset, not a share of worldwide unique passengers, because IATA's country-market definition counts international journeys at both origin and destination.

15.9 Aviation intensity and productivity indicators

Indicator	Scientific formula	Interpretation
Passengers per capita	PAX / Population	Aviation consumption relative to

		population
Airports per million people	Airports / Population $\times 10^6$	Infrastructure availability
Airport density	Airports / land area $\times 100,000$	Spatial infrastructure density
Passengers per airport	Airport PAX / commercial airports	Average infrastructure utilization
Cargo intensity	Cargo tonnes / GDP	Cargo scale relative to economy
Aviation GDP share	Aviation GDP / national GDP $\times 100$	Economic dependence/intensity
Route density	Routes / commercial airports	Network breadth per airport
Internationalization	International PAX / total PAX $\times 100$	International orientation
Fleet intensity	Aircraft / population $\times 10^6$	Fleet capacity relative to population
Employment intensity	Aviation jobs / labour force $\times 100$	Labour-market relevance

15.10 Standardization and composite-index mathematics

Because GADI combines variables with different units, raw observations should first be standardized. For variable x , $Z_i = (x_i - \bar{x})/s_x$. Directionally adverse indicators, if any, should be reverse-coded before aggregation. The PCA specification is $GADI_i = \sum w_j Z_{ij}$, where weights are derived from empirically retained components rather than selected to create a desired country ordering.

For communication, a min-max transformation may be used after estimation: $GADI_{0-100} = 100 \times (GADI_i - GADI_{min}) / (GADI_{max} - GADI_{min})$. Sensitivity should be tested against equal weights and leave-one-dimension-out specifications.

15.11 PCA adequacy and reliability

Before PCA, sampling adequacy should be assessed with the Kaiser-Meyer-Olkin statistic and Bartlett's test of sphericity. Component retention should consider eigenvalues, scree-plot evidence, parallel analysis where feasible, explained variance and conceptual interpretability. High-loading duplicate variables should be screened for redundancy. The manuscript should report loadings and communalities rather than only the final index scores.

15.12 Panel elasticity model

A log-log fixed-effects specification permits elasticity interpretation: $\ln(PASS_{it}) = \beta_0 + \beta_1 \ln(GDPPC_{it}) + \beta_2 \ln(POP_{it}) + \beta_3 \ln(AIRPORTS_{it}) + \beta_4 \ln(TOUR_{it}) + \mu_i + \lambda_t + \varepsilon_{it}$. Under the model assumptions, β_1 represents the estimated percentage change in passenger activity associated with a 1% change in GDP per capita, holding included covariates and fixed effects constant.

For cargo: $\ln(CARGO_{it}) = \alpha_0 + \alpha_1 \ln(TRADE_{it}) + \alpha_2 \ln(GDP_{it}) + \alpha_3 \ln(CONNECT_{it}) + \alpha_4 \ln(AIRPORTS_{it}) + \mu_i + \lambda_t + \varepsilon_{it}$. Country-clustered robust standard errors should be considered because repeated observations within countries are unlikely to be independent.

15.13 Dynamic and lagged specifications

Aviation demand can respond to macroeconomic conditions with delays. A dynamic extension is $\ln(PASS_{it}) = \rho \ln(PASS_{i,t-1}) + \beta X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$. Because inclusion of a lagged dependent variable can bias conventional fixed-effects estimators in short panels, a dynamic-panel estimator such as difference or system GMM may be considered only if the final data structure and instrument diagnostics justify it. Instrument proliferation, Hansen/Sargan tests and serial-correlation diagnostics must be reported if GMM is used.

15.14 Forecast mathematics and scenario discipline

ACI forecasts 18.8 billion airport passengers by 2045 from the 9.8 billion 2025 base. The implied 20-year endpoint CAGR is $(18.8/9.8)^{(1/20)} - 1 = 0.03\%$ per year. This is a derived growth rate from ACI's forecast endpoints, not an independent forecast produced by this study.

Scenario calculations should use $P_t = P_0(1+g)^t$, with separate baseline, constrained and sustainability-transition growth assumptions. Forecast sensitivity can be expressed as $\Delta P/\Delta g$ across plausible growth rates. Forecast intervals should be produced only when a statistical forecasting model is estimated from time-series data.

15.15 Scientific calculation summary

Calculation	Result	Status
Mean passenger journeys per ACI-covered airport	3.479 million	Derived from final 2025 ACI totals
Top-20 airport concentration (CR20)	16.22%	Derived
Traffic outside top 20	83.78%	Derived
Top-3 airport share of global 2025 traffic	2.99%	Approx. derived
2019–2025 endpoint traffic CAGR	1.06% p.a.	Derived; disrupted period
Direct-job share of supported jobs	13.41%	Derived from ATAG 2023
Tourism-job share of supported jobs	43.12%	Derived from ATAG 2023
Total/direct economic-impact ratio	3.73×	Accounting ratio
Aviation share of human CO ₂	2.05%	Derived from ATAG 2023
Aggregate CO ₂ per RPK	108.0 g/RPK	Broad aggregate ratio
ACI 2025→2045 forecast endpoint CAGR	0.03% p.a.	Derived from ACI forecast endpoints

16. Empirical Cross-Sectional PCA and Cluster Analysis

To replace purely hypothetical numerical output with a reproducible empirical demonstration, this section analyses the 13 country markets for which the manuscript contains verified IATA 2025 passenger-market size and year-on-year growth observations: the ten largest country markets plus Kazakhstan, Uzbekistan and Vietnam. This is deliberately identified as a 2025 cross-sectional market analysis, not as the final multidimensional GADI PCA and not as a 2015–2025 panel model.

16.1 Input data

Country	2025 passengers (m)	YoY growth (%)
United States	890.1	1.6
China	776.1	4.8
United Kingdom	269.7	3.4
Spain	252.7	5.0
Japan	223.5	9.2
India	218.2	3.3
Italy	187.3	5.8
Germany	163.8	3.4
France	152.6	2.2
Türkiye	129.3	2.9
Kazakhstan	18.1	40.0
Uzbekistan	12.5	16.9
Vietnam	80.9	14.8

16.2 Standardization and PCA

Passenger-market size and annual growth were standardized to zero mean and unit variance before PCA. With two standardized variables, PC1 explains 71.86% of total variance and PC2 explains 28.14%. The PC1 loading vector is approximately (+0.707 for market size, −0.707 for growth), so the first component contrasts scale with rapid growth. PC2 loads positively on both variables (+0.707, +0.707), capturing their common high-value direction.

Component	Explained variance (%)	Cumulative (%)	Loading: passengers	Loading: growth
PC1	71.86	71.86	0.707	-0.707
PC2	28.14	100.00	0.707	0.707

KMO and Bartlett diagnostics are not reported for this two-variable demonstration because they are intended for assessing factorability in a genuinely multivariate indicator set. Reporting artificial KMO/Bartlett values here would overstate the evidence. Those diagnostics remain required for the later full GADI indicator matrix.

16.3 Cluster selection

Number of clusters (k)	Silhouette score
2	0.635
3	0.668

4	0.661
5	0.462

Among $k = 2-5$, the highest silhouette score is 0.668 at $k = 3$. A three-cluster k-means solution was therefore retained for this limited two-variable market illustration. K-means used standardized inputs, 50 initializations and a fixed random seed for reproducibility.

16.4 Country cluster memberships

Country	Passengers (m)	Growth (%)	PC1	PC2	Cluster
France	152.6	2.2	0.161	-0.749	1
Germany	163.8	3.4	0.108	-0.634	1
India	218.2	3.3	0.264	-0.492	1
Italy	187.3	5.8	0.005	-0.402	1
Japan	223.5	9.2	-0.133	-0.065	1
Spain	252.7	5.0	0.240	-0.278	1
Türkiye	129.3	2.9	0.048	-0.764	1
United Kingdom	269.7	3.4	0.399	-0.343	1
Uzbekistan	12.5	16.9	-1.250	-0.107	1
Vietnam	80.9	14.8	-0.916	-0.066	1
Kazakhstan	18.1	40.0	-2.848	1.521	2
China	776.1	4.8	1.692	1.145	3
United States	890.1	1.6	2.229	1.235	3

Cluster 3 contains the United States and China and is characterized by exceptionally high passenger-market scale with comparatively moderate growth. Cluster 2 contains Kazakhstan alone because its 40.0% growth rate is a strong standardized outlier in this sample. Cluster 1 contains the remaining ten markets, including several mature medium-to-large markets and the fast-growing Uzbekistan and Vietnam. The breadth of Cluster 1 confirms that a two-variable classification is insufficient for a definitive aviation-development taxonomy and supports the manuscript's proposed multidimensional GADI/ABEI/AEI framework.