

REDUCING AIRLINE EMISSIONS INTENSITY WITH POLICY PACKAGES: A COMPARATIVE SYNTHESIS

REDUÇÃO DA INTENSIDADE DE EMISSÕES DE COMPANHIAS AÉREAS COM PACOTES DE POLÍTICAS: UMA SÍNTESE COMPARATIVA

Article received on: 13/6/2025

Article accepted on: 21/8/2025

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The authors declare that there is no conflict of interest

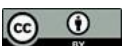
Abstract

This study examines how multi-layered policy packages relate to airline emissions intensity, measured as carbon dioxide per revenue passenger-kilometre (CO₂/RPK), for 2010–2025. A semi-systematic evidence synthesis and comparative policy analysis are employed. Five indicators are operationalised: cross-regime alignment, effective carbon price, Sustainable Aviation Fuel (SAF) adoption, monitoring–reporting–verification (MRV) capacity, and access to green finance. Results indicate that stronger alignment and coverage, higher effective carbon prices, and scaled drop-in SAF are directionally associated with lower CO₂/RPK; robust MRV and finance channels amplify these links. Operational optimisation in descent profiles and routing provides complementary short-term gains, whereas cross-regime differences can raise compliance costs. An implementation roadmap is outlined: operations, long-term multi-source SAF portfolios, green financing, and MRV automation. Reliance on secondary sources and directional inference is acknowledged as a limitation. The framework provides a practical basis for reading instrument mixes against CO₂/RPK and for designing policy-aligned, cost-aware transition strategies.

Keywords: Airline Emissions Intensity. Sustainable Aviation Fuel. Carbon Pricing. Emissions Monitoring. Emissions Verification. Emissions Trading System.

Resumo

Este estudo examina como pacotes de políticas multifacetados se relacionam com a intensidade das emissões das companhias aéreas, medidas como dióxido de carbono por passageiro-quilômetro pago (CO₂/RPK), para o período de 2010 a 2025. Uma síntese de evidências semisistemática e uma análise comparativa de políticas são empregadas. Cinco indicadores são operacionalizados: alinhamento entre regimes, preço efetivo do carbono, adoção de Combustível de Aviação Sustentável (SAF), capacidade de monitoramento-relatório-verificação (MRV) e acesso a financiamento verde. Os resultados indicam que alinhamento e cobertura mais fortes, preços efetivos de carbono mais altos e SAF em escala estão associados direcionalmente a menores CO₂/RPK; canais robustos de MRV e financiamento amplificam essas ligações. A otimização operacional em perfis de descida e rotas proporciona ganhos complementares de curto prazo, enquanto diferenças entre regimes podem aumentar os custos de conformidade. Um roteiro de implementação é delineado: operações, portfólios de SAF de múltiplas fontes de longo prazo, financiamento verde e automação de MRV. A dependência de fontes secundárias e inferência direcional é reconhecida como uma limitação. A estrutura fornece uma base prática para a análise de combinações de instrumentos em relação ao CO₂/RPK e para a elaboração de estratégias de transição alinhadas às políticas e com foco em custos.



Palavras-chave: Intensidade de Emissões de Companhias Aéreas. Combustível Sustentável para Aviação. Precificação de Carbono. Monitoramento de Emissões. Verificação de Emissões. Sistema de Comércio de Emissões.

1 INTRODUCTION

Global climate targets necessitate a rapid transformation of aviation's carbon-intensive structure. By bridging aviation management and international climate governance, a clear and measurable framework is offered to read how multi-layered regulations shape managerial decisions and emissions intensity (CO₂/RPK). The framework is applied to **2010–2025**.

Contributions are fourfold. First, the governance–market–operations nexus is operationalized through five indicators—Regime Alignment Index (RAI), Carbon Price Pressure (CPP), SAF Adoption Intensity (SAFAI), MRV Capacity (MRVC), and Green Finance Access (GFA). Second, a comparative policy/mechanism matrix (T6) is assembled juxtaposing CORSIA, the EU Emissions Trading System (EU ETS)/Carbon Border Adjustment Mechanism (CBAM), and ReFuelEU to clarify compliance cadences and cross-regime effects. Third, through a semi-systematic evidence synthesis, stronger alignment, clearer price signals, and scaled drop-in SAF are directionally linked to lower CO₂/RPK, with MRV maturity acting as a multiplier. Fourth, these insights are translated into an implementation roadmap—operations (Continuous Descent Operations/Optimized Profile Descent, CDO/OPD), long-term multi-source SAF portfolios, green/performance-linked financing, and MRV automation—so that policy packages can be internalized as cost-aware transition strategies.

Aviation firms operate under phased international and EU instruments that jointly set blending, reporting, and pricing cadences—CORSIA, ReFuelEU, and EU ETS/CBAM. These instruments shape fuel-mix choices, cost signals, and compliance planning while creating cross-regime coordination challenges—the managerial problem addressed by the framework.

The study asks: (i) through which mechanisms do CORSIA, EU ETS/CBAM, and ReFuelEU affect CO₂/RPK and operational practices; (ii) how can these effects be tracked with the T5 indicators; and (iii) do the findings support the direction of hypotheses H1–

H5? A semi-systematic evidence synthesis is combined with comparative policy analysis. No new data are produced and no effect sizes are estimated; only measurements and provisions explicitly reported in reliable sources are compiled and interpreted directionally to preserve replicability for decision-makers.

Preliminary findings indicate that as regime alignment and scope increase (RAI), the effective carbon price strengthens (CPP) and SAF adoption scales (SAFAI), such that emissions intensity declines directionally; robust MRVC and accessible finance/incentive channels (GFA) amplify these links. Operational measures (CDO/OPD) provide complementary short-term gains, whereas cross-regime timeline/method differences can raise compliance costs. Section 2 reviews the literature; Section 3 presents theory and hypotheses; Section 4 details method and measurement standards; Section 5 reports findings via T5–T6; Section 6 discusses implications; and Section 7 concludes with recommendations.

2 LITERATURE REVIEW

2.1 Theoretical lenses and synthesis

A policy-mix that co-designs carbon pricing, SAF policies/mandates, and operational/engineering standards delivers more effective mitigation than single instruments; price signals create incentives while technology/standards policies reduce adoption frictions and leakage risks (Bergh *et al.*, 2021; Rogge & Reichardt, 2016; Champeecharoensuk *et al.*, 2023; Mannhardt *et al.*, 2024). In aviation, aligning the EU ETS/CORSIA with ReFuelEU, plus Air Traffic Management (ATM)/CDO/OPD, is expected to lower CO₂/RPK, with effect size conditioned by coverage and MRV discipline (EASA, 2022; Maertens *et al.*, 2019; EU, 2023a; ICAO, 2025). Integrated mixes outperform single instruments; pricing is complementary, not sufficient (Axsen, 2020). Coordination is pivotal: misaligned scope/timing harms performance, while harmonized, service-normalized metrics and robust MRV—especially CORSIA–EU ETS alignment—reduce duplication and stabilize incentives (Wiedemann & Ingold, 2021; Matthes *et al.*, 2017; Maertens *et al.*, 2019; Arévalo, 2023).

Carbon pricing is the behavioural backbone; strong MRV (EU Monitoring and Reporting Regulation (MRR) 2018/2066; CORSIA Annex 16 Vol. IV) improves

measurement reliability and sharpens pass-through to firm-level CO₂/RPK (EU, 2018; ICAO, 2025; Rădulescu *et al.*, 2024). Conversely, fragmented governance across CORSIA–EU ETS–ReFuelEU can add dual-reporting/transaction costs that dilute the signal (Anselmi, 2023; Budak, 2025; Maertens *et al.*, 2019).

ReFuelEU’s rising SAF shares and Renewable Fuels of Non-Biological Origin (RFNBO) sub-targets, the 90% uplift rule, and the EU Union Database increase demand certainty and traceability; ASTM D7566 drop-in pathways make substitution feasible (EU, 2023a; EASA, 2022; IATA, 2024; ICAO, 2024). Green/SLB bonds and §40B/§45Z tax credits can narrow short-run cost premia; techno-economic studies show SAF costs are highly sensitive to financing, reinforcing near-term uptake (ESMA, 2025; Hooda & Yadav, 2023; U.S. DOE, 2025; Collis *et al.*, 2022; Trejo-Pech *et al.*, 2019).

In sum, the expectation RAI↑–CPP↑–SAFAI↑ → CO₂/RPK↓ is strengthened when MRVC sharpens the price channel and GFA provides a short-term cost bridge. This theoretical synthesis underpins a unified reading of Section 2.1’s evidence on operational efficiency and SAF pathways/blend limits under a common measurement standard, and clarifies the directional links for H2 (CPP×MRVC), H3 (GFA→SAFAI), H5 (fragmented governance) while tying into RQ1–RQ3 (Afşar *et al.*, 2023; IATA, 2024; ICAO, 2025; Tan *et al.*, 2022; OECD, 2024).

2.2 Studies on sustainability in aviation management

In aviation, sustainability reduces emissions and cost pressures through fuel efficiency, Sustainable Aviation Fuels (SAF), route/profile optimization, and airport energy projects. Fuel accounted for approximately 22–24% of airlines’ total costs pre-pandemic (IATA, 2019), rising to 31.8% in 2023 (IATA, 2025). Even small efficiency gains reduce fuel burn, lowering CO₂/RPK and—via the fuel-cost channel—operating expenses (Cho *et al.*, 2020; Budd & Suau-Sánchez, 2016). However, efficiency steps alone are not sufficient; in the medium to long term, the SAF transition appears decisive. Among ASTM D7566 pathways, HEFA-SPK and FT-SPK are most scalable via 50% drop-in compatibility and, owing to mature supply structures, are the most amenable to near-term scaling, whereas limited-aromatic pathways face blend constraints requiring further investment (IATA, 2024; ICAO, 2025; EASA, 2022). For pathways and blend limits, see Table 1.

Operationally, route/profile optimization and OPD can reduce fuel use by 3.9%–40% (Aydoğan & Çetek, 2022; Tian *et al.*, 2019; Ryerson *et al.*, 2015; Şafak *et al.*, 2017; Şafak *et al.*, 2018; Ahmed *et al.*, 2021). Despite airspace constraints, digitalization investments increase route flexibility. In ground handling, shifting from diesel to e-GSE reduces maintenance outlays and fuel expenses and—via emissions-compliance alignment—lowers regulatory risk (Yıldız *et al.*, 2023). On the financial front, instruments such as green bonds and net-zero commitments can lower the cost of capital (“greenium”) (Wulandari *et al.*, 2018). Overall, concurrent fuel efficiency, SAF, operational optimization, and airport energy projects can meet emission and cost goals, though SAF costs, supply asymmetries, and regional policy differences constrain scaling (IATA, 2024; ICAO, 2025).

Table 1.

SAF production pathways and blend limits — ASTM D7566–approved routes

Production pathway (short name)	ASTM D7566 annex (full name)	Max. blend (%)	Typical feedstocks	Short note
FT-SPK	Annex A1 – Fischer–Tropsch SPK	50	Coal, natural gas, biomass	Contains no aromatics; aromatics are needed in the blend for elastomer compatibility.
HEFA-SPK	Annex A2 – Hydroprocessed Esters and Fatty Acids SPK	50	Vegetable/animal oils, Used Cooking Oil (UCO)	Most mature commercial pathway; broad capacity.
SIP	Annex A3 – Synthesized Iso-Paraffins	10	Fermented sugars	10% limit due to lack of aromatics.
FT-SKA	Annex A4 – FT Synthetic Kerosene w/ Aromatics	50	Coal, natural gas, biomass	Contains aromatics; improves compatibility.
ATJ-SPK	Annex A5 – Alcohol-to-Jet SPK	50	Ethanol, isobutanol	High blend ratio; meets quality parameters.
CHJ	Annex A6 – Catalytic Hydrothermolysis Jet	50	Vegetable/waste oils, UCO	ASTM-approved; high energy density.
HC-HEFA-SPK	Annex A7 – HEFA from Algal Oils	10	Algal oils	10% limit due to lack of aromatics.
ATJ-SKA	Annex A8 – Alcohol-to-Jet SKA (with aromatics)	50*	C2–C5 bio-alcohols	Contains aromatics. IATA upper limit 50%.

*Upper limit per IATA; ASTM blend limit as specified in Annex A8.

Source: ICAO (2025); ICAO (2024); ICAO (2023); EASA (2022); IATA (2024); ICAO, 2023b).

Table 2.*SAF capacity, cost, and investment requirements — selected years/regions*

Year / Region	Capacity (Mt/year)	Cost (USD/gal)	Investment (USD billions)	Short note
2025 – Global	1.0–1.5	4.00–6.00	20–25	HEFA-heavy early scaling
2030 – Global	8–12	3.00–5.00	150–200	FT and ATJ come online
2040 – Global	50–60	2.00–4.00	800–950	Large-scale biomass and e-fuel
2050 – Global	300+	1.50–3.00	3,000+	Net-zero scenario
2025 – North America	0.6–0.8	3.50–5.00	10–12	Effect of federal tax credit
2030 – North America	3–4	3.00–4.50	45–60	New HEFA and ATJ plants
2025 – Europe	0.3–0.4	4.50–6.00	6–8	Fit-for-55 compliance mandates
2030 – Europe	2–3	3.50–5.00	35–50	CBAM and SAF blending targets

Ranges are directional and compiled from the cited sources

Source: IATA (2024); ICAO (2025, Environment Report); ICAO (2025, LTAG Data); U.S. DOE (2025).

2.3 International climate governance

Global (International Civil Aviation Organisation (ICAO)/United Nations Framework Convention on Climate Change (UNFCCC)) and regional (EU Fit-for-55, CBAM) frameworks deepen debates over equity and compliance costs. CORSIA provides a global baseline for offsetting/reducing international flight emissions but continues to be criticized on “historical responsibility” and “differentiated capability” grounds (Anselmi, 2023; ICAO, 2022; ICAO, 2023a). Differences in MRV maturity and limited financial/institutional capacity increase compliance risk and transaction costs (Guan *et al.*, 2022; Baumber *et al.*, 2021; EASA, 2022; ICAO, 2024). In the EU, removal of free allocation under the EUETS and ReFuelEU’s SAF blending mandates differentiate costs across carriers, while CBAM—though not covering aviation fuel—may indirectly raise costs via energy-intensive inputs, with potential pass-through to fares and connectivity (EU, 2023b; Chu *et al.*, 2024). Asynchronous timelines and metrics create uncertainty and dual-reporting burdens; evidence from the EUETS (2012–2020) shows added costs, margin pressure for low-cost models, and price advantages for non-covered competitors (Budak, 2025; EASA, 2022; ICAO, 2023b; Scheelhaase *et al.*, 2012; Barbot *et al.*, 2014; Schaefer *et al.*, 2010). While the Paris Agreement envisions long-term reductions, CORSIA focuses on offsetting post-2020 growth; Table 3 summarises the

objectives, scope, timelines, and compliance mechanisms of CORSIA, Fit-for-55, and CBAM. Additional policy is therefore needed to bend the emissions curve, informing H5 (fragmentation → compliance cost) (Maertens *et al.*, 2019; Hjerpe & Nasiritousi, 2015).

Table 3.

CORSIA, Fit-for-55, and CBAM — objectives, scope, and compliance mechanisms

Regime	Objective	Scope	Start	Compliance mechanism	Enforcement/Implementation	Expected directional effect (→ CO ₂ /RPK)
CORSIA (ICAO)	Offsetting/reducing international aviation emissions	State-to-state flights (domestic excluded)	Pilot: 2021–23; Phase 1: 2024–26; Phase 2: 2027+	Emissions reporting, carbon credits	ICAO oversight; inter-state supervision	RAI↑ → CO ₂ /RPK↓; MRVC↑ → signal effect↑
Fit-for-55 (EU) (EU ETS + ReFuelEU)	Alignment with EU climate targets; multi-sector incl. aviation	Intra-EU and EU–third country flights (EU ETS/ReFuelEU)	From 2021 → phased	Auctioning in EU ETS; SAF blending mandates	European Commission and national authorities	CPP↑ → CO ₂ /RPK↓; SAFAI↑ → CO ₂ /RPK↓; MRVC↑ → effect↑
CBAM (EU)	Preventing carbon leakage	Imports of iron & steel, cement, aluminum, fertilizers, etc.	Transition: 2023–25; full: 2026	Carbon certificate at import	European Commission and customs	Indirect CPP↑ → CO ₂ /RPK↓ (via supply chain)

Sources: ICAO (2022 A41-21; 2023 A41-20); EASA (2022); EU (2023); ICAO (2024, SAF).

2.4 Critical assessment and research gaps

The theoretical case for policy mixes—combining carbon pricing with technology and standards policies—outperforming single instruments is well established (Rogge & Reichardt, 2016; Bergh *et al.*, 2021; Champeecharoensuk *et al.*, 2023; Mannhardt *et al.*, 2024). Yet in aviation, firm-level evidence linking such mixes to emissions intensity (CO₂/RPK) remains limited; in some configurations EUETS coverage aligns with non-decreasing emissions, highlighting sensitivity to instrument design and scope (Afşar *et al.*, 2023). Much work on EUETS–CORSIA–ReFuelEU interoperability stays at the regime level; the moderating role of MRV is rarely modeled explicitly in firm-level frameworks (EU, 2018; Maertens *et al.*, 2019; ICAO, 2025; Rădulescu *et al.*, 2024; Eichinger *et al.*, 2025). Timing/methodology misalignments can generate double-reporting and compliance costs, weakening signal continuity (Maertens *et al.*, 2019;

Anselmi, 2023; Budak, 2025; Arévalo, 2023). CBAM can also shift input costs and supplier choices along value chains, implying indirect competitiveness effects (Bardow *et al.*, 2025; Fu *et al.*, 2025).

On operational measures (ATM, CDO/OPD), reported fuel/CO₂ savings are highly context-dependent, limiting generalizability; constrained settings often yield 1–3% gains, while flexible configurations can approach 9% (EASA, 2022; Aydoğan & Çetek, 2022; Coppenbarger *et al.*, 2012; Liu *et al.*, 2021; Boucher *et al.*, 2023). This variance underscores the need for harmonized, service-normalized metrics (e.g., CO₂/RPK) and consistent reporting rules.

On SAF, ReFuelEU's minimum shares, RFNBO sub-targets and traceability provisions institutionalize substitution pathways (EU, 2023a; EASA, 2022; IATA, 2024; ICAO, 2024). Yet while green/SLB bonds and §40B/§45Z-type credits can compress near-term cost premia, firm-level causal links from finance to offtake/blend shares → CO₂/RPK are seldom quantified; techno-economic studies show strong cost sensitivity to capital/discount assumptions, but translation to airline intensity outcomes is thin (Hooda & Yadav, 2023; ESMA, 2025; U.S. DOE, 2025; Collis *et al.*, 2022; Trejo-Pech *et al.*, 2019; Capaz *et al.*, 2020).

Summary of gaps: (i) Joint, firm-level testing of CPP, SAFAI, operations, and RAI vs. CO₂/RPK under a shared standard is missing; (ii) MRVC rarely appears as an explicit moderator; (iii) GFA → SAFAI → CO₂/RPK lacks robust quantification; (iv) CBAM's supply-chain effects on airline costs are not systematically measured. These gaps motivate the subsequent variables and hypotheses.

3 THEORETICAL FRAMEWORK AND HYPOTHESES

3.1 Positioning: Firm response under multi-layered climate governance

The Paris Agreement aims to limit global warming to well below 2 °C, preferably to 1.5 °C, and envisages a transition to net zero “in the second half of the century” (UNFCCC, 2015). International flights are governed under ICAO separately from UNFCCC national inventories; ICAO's Long-Term Global Aspirational Goal (LTAG) and its “basket of measures” approach (technology, operations, SAF/ Low-Carbon Aviation Fuel (LCAF), market-based measures) constitute this framework (ICAO, 2022;

ICAO, 2025). In market-based measures, CORSIA operates in phases—2021–2023 pilot, 2024–2026 first, and 2027–2035 second (ICAO, 2023b).

On the EU side, ReFuelEU Aviation raises minimum SAF blend ratios toward 2% in 2025, 6% in 2030, 20% in 2035, and 70% in 2050; it constrains “tankering” (fuel tankering (uplifting extra fuel to avoid refuelling elsewhere) behavior and sets sub-targets for synthetic fuel (EU, 2023b). CBAM establishes a border adjustment regime complementing the EUETS, with reporting in 2023–2025 and a certificate obligation from 2026 onward; MRV processes are standardized under EU MRR 2018/2066 (EU, 2018; EU, 2023b). In capital-markets governance, European Securities and Markets Authority (ESMA) strengthens information quality and comparability by clarifying the framework for external reviewers in green/transition bonds and SLBs (ESMA, 2025). In the United States, §40B SAF and §45Z Clean Fuel Production credits function as the main financial channels incentivizing SAF/clean-fuel production and adoption (U.S. DOE, 2025).

As schedule–methodology alignment across these structures and access to finance increase, airlines are expected to reduce emission intensity more cost-effectively; otherwise, fragmentation and weak MRV are likely to dilute effectiveness under the same price signal (ICAO, 2025; EU, 2023b).

3.2 Theoretical basis: global governance, liberal environmentalism, and a “conflictual architecture”

The delegation of UNFCCC/Kyoto authority to ICAO generated a “conflictual climate governance” by causing the CBDR (common but differentiated responsibilities) principle to collide with non-discrimination/equal treatment principles within the same sector (Anselmi, 2023). The phased transition of CORSIA from voluntary to mandatory participation and the blend of sectoral average/operator growth trigger equity–efficiency tensions that tend to raise relative marginal costs for fast-growing or new entrants (Anselmi, 2023). The impact of differences in regime design (base year, scope, offset effectiveness) on net abatement outcomes has been shown in comparative studies (Maertens *et al.*, 2019).

3.3 Impact mechanisms

The price signal incentivizes abatement via the effective carbon price stemming from the EUETS/CBAM; the accuracy of MRV amplifies the behavioural effect of this signal (EU, 2018; EU, 2023b; OECD, 2024). SAF “drop-in” substitution can be integrated into fleets and the supply chain without major infrastructure changes thanks to the approved pathways under ASTM D7566; ReFuelEU’s volume targets may narrow the cost differential over time by generating demand certainty (IATA, 2024; ICAO, 2024; EU, 2023b). Operational efficiency reduces CO₂ intensity through CDO/OPD and route/profile optimization, and these gains become trackable via MRV (EASA, 2022; ICAO, 2025). Financing channels (green/transition bonds, SLBs, §40B/§45Z tax incentives) ease the CAPEX–OPEX burden; by improving information quality, the ESMA framework can enhance investor confidence and lower financing costs via the “greenium” (ESMA, 2025; U.S. DOE, 2025; OECD, 2018; OECD, 2022; OECD, 2024).

3.4 Concepts and operationalization

The indicators below present the operational definition, measurement, and expected sign of effect on CO₂/RPK for the concepts to be used in the analysis.

Table 4.

Operationalization of theoretical concepts: definitions and measurements

Concept	Operational definition	Measurement / Variable	Expected sign	Example source
RAI	Composite score of CORSIA phase participation + EUETS coverage + ReFuelEU target alignment + CBAM transition/certificate	0–1 index (composite)	↓	ICAO (2025); EU (2023)
CPP	Route-weighted effective carbon price differential for origin/destination	€/tCO _{2e} differential	↓	OECD (2024)
SAFAI	SAF blend %, annual SAF (GJ), and/or presence of an LTA	%; GJ/year; (0/1)	↓	EU (2023); IATA (2024)
MRVC	Alignment with CORSIA Annex 16 Vol. IV and EU MRR 2018/2066	MRV maturity score	(amplifies effect)	EU (2018); ICAO (2025)
GFA	Use of green/transition bonds–SLBs; ESMA framework; access to §40B/§45Z	Issuance/stock; reviewer quality; (0/1)	(reduces cost effect)	EU (2025); OECD (2024); U.S. DOE (2025)

Concept	Operational definition	Measurement / Variable	Expected sign	Example source
DV (Dependent Variable)	Emission intensity	CO ₂ /RPK (CO ₂ /Available Seat-Kilometre (ASK) where necessary)	—	ICAO (2025)

Note: Expected signs are for the effect on CO₂/RPK; “↓” denotes a decrease, “↑” an increase.

Source: Authors

3.5 Hypotheses

H1 (Regime alignment → Emissions): As RAI increases, CO₂/RPK decreases; schedule–methodology consistency is expected to reduce uncertainty and transaction costs (ICAO, 2025; EU, 2023b).

H2 (Carbon price → Emissions; MRV moderation): As CPP increases, CO₂/RPK decreases; this effect strengthens when MRVC is high (EU, 2018; OECD, 2024).

H3 (SAF → Emissions & cost; finance moderation): As SAFAI increases, CO₂/RPK decreases; the short-term cost increase is softened when GFA and/or §40B/§45Z are high (IATA, 2024; EU, 2023b; U.S. DOE, 2025; ESMA, 2025).

H4 (Operational optimization): As CDO/OPD and route/profile optimization increase, CO₂/RPK decreases; the RAI × Operations interaction is expected to be negative (EASA, 2022; ICAO, 2025).

H5 (Fragmentation → Compliance cost): As regime fragmentation increases, the compliance cost/revenue ratio rises; dual MRV (CORSA + EU MRR) may impose a disproportionate burden on small/medium-sized carriers (Anselmi, 2023; EU, 2018; ICAO, 2025).

3.6 Boundary conditions and alternative explanations

Market structure, fuel price volatility, incentive asymmetries, and measurement error risk may affect the estimated relationships. Cost pass-through and demand elasticity may differ in hub-intensive versus point-to-point networks (EASA, 2022). Shocks in fossil jet fuel can widen or narrow the SAF margin differential (IATA, 2024). Regional tax credits and supports may render the GFA indicator heterogeneous (U.S. DOE, 2025; OECD, 2022). Low MRV maturity can distort the measured effect of the effective carbon price and operational gains; CORSA–EUETS design differences (base, scope, offset

effectiveness) can markedly shape policy outcomes (EU, 2018; ICAO, 2025; Maertens *et al.*, 2019).

3.7 Theoretical contribution and expected result

The framework (i) conceptualizes an effective policy mix within the regime alignment–price signal–technology pathway triangle, (ii) explains the multiplier effect of MRV on the price signal, and (iii) shows that SAF access together with green finance/tax credits are enabling conditions for firm-level transition. Our expectation is that the combination of high RAI + high MRVC + high SAFAI + accessible GFA/incentives will deliver a significant decrease in CO₂/RPK and competitive neutrality (ICAO, 2025; EU, 2023b; OECD, 2024; IATA, 2024; U.S. DOE, 2025).

4 METHOD / RESEARCH DESIGN

This study employed a semi-systematic evidence synthesis combined with comparative policy analysis, organizing verifiable findings thematically and reading them directionally via the framework indicators (Regime Alignment Index, Carbon Price Pressure, SAF adoption intensity, MRV capacity, Green Finance Access) against CO₂/RPK. No new data were produced, no statistical estimation was conducted, and no causal claims were made; quantitative values were reproduced verbatim from sources. The scope covered peer-reviewed studies and official/semi-official reports on airline/airport operations, SAF policies, carbon pricing, and MRV regimes for 2010–2025, with earlier “foundational” texts included only with theoretical justification. Sources were searched on Scopus, Web of Science, Google Scholar, and institutional repositories using standard keywords; title–abstract pre-screening, full-text review, and forward–backward citation chaining were applied. Inclusion required aviation focus, measurable outputs, clear methodology, and verifiable sources; opinion/grey content, purely engine/chemical technique without sectoral impact, and studies with unspecified methods were excluded. Research questions asked: RQ1. Through which mechanisms, as reported in the literature, do the CORSIA, EUETS/CBAM, and ReFuelEU regimes affect CO₂/RPK and operational practices, and how can these effects be explained? RQ2. How have these effects been tracked with supportable indicators via the concepts RAI, CPP,

SAFAI, MRVC, and GFA defined in theory? RQ3. Do the findings support the direction of hypotheses H1–H5?

4.1 Operationalization (supportable indicators only)

The concepts in theory (RAI, CPP, SAFAI, MRVC, GFA) and the findings of Section 2 were coded as directional evidence according to the measurement standards in Table 5 (T5). Each claim was first mapped to the relevant concept, then only measurements/texts explicitly reported in the source were taken. The interpretation is directional, not causal.

The dependent variable is CO₂/RPK: it is widely accepted in aviation, ensures comparability, and incorporates the effect of load factor. Calculation rule: CO₂ = 3.16 × fuel (kg); RPK is based on great-circle distance, and fuel consumption was taken according to the actually flown distance (Air Traffic Management (ATM) horizontal inefficiency was reflected). Studies using a different definition were footnoted; inconsistent ones were excluded.

The following were not included due to insufficient evidence: (i) claims for which no numerical value or measurement definition is provided, (ii) measurements with no counterpart in Table 5 (T5), (iii) statements with unclear source/no citation, (iv) intensity/measurements incompatible with the methodological standard.

Table 5

(T5). Operationalization of concepts used in the study — measurement standard and coding thresholds

Concept	Operational definition	Unit/Scale	Measurement / Variable	Timing	Expected sign	Example source(s)	Coding / Threshold
RAI	CORSIA phase participation + EUETS coverage + ReFuelEU target alignment + CBAM status (composite)	0–1 index	Component scores → weighted sum	t	↓	ICAO (2025); ICAO (2023); EU (2018); EU (2023); EU (2023c)	Weights: EUETS 0.40, CORSIA 0.40, ReFuelEU 0.10, CBAM 0.10. Score (0/0.5/1) = no/partial/full coverage. ReFuelEU applies only in the EU-departing context.

Concept	Operational definition	Unit/Scale	Measurement / Variable	Timing	Expected sign	Example source(s)	Coding / Threshold
CPP	Net Effective Carbon Rate for origin–destination (€/tCO _{2e}) and coverage	€/tCO _{2e} ; %	(i) Country Net (Effective Carbon Rate) ECR, (ii) ECR _{origin} – ECR _{destination} , (iii) Positive ECR coverage (%) → RPK-weighted	t	↓	OECD (2024; 2022); EU (2018; 2023b; 2023c)	Network-level route differential and coverage average; CBAM effect indirect (inputs/supply).
SAFAI	SAF blend % / annual SAF (GJ) / long-term supply (LTA)	%; GJ; 0–1	Energy-based blend % (primary) or GJ/year; LTA = 1 if offtake exists	t–1	↓	EU (2023); IATA (2024); ICAO (2024)	RFNBO sub-targets: 2030 1.2%, 2035 5%, 2050 35%; total SAF: 2025 2% → 2050 70%. Book-and-claim accepted; no double counting.
MRVC	Mean of 6 subcomponents: (1) Monitoring Plan, (2) Data control & risk, (3) Data gap management, (4) Record & verified report, (5) Verification & improvement, (6) CORSIA compliance	0–1 index	Each subcomponent 0/0.5/1 → average	t	(amplifies effect)	EU (2018); ICAO (2025); ICAO (2023)	1 point: approved MP; documented control & risk; data gaps ≤5% (or if >5% then notification + improvement); ≥10 years archiving & verified report by 31 March; verification per 2018/2067; up-to-date CORSIA CERT/CCR/CEF.
GFA	(i) Greenium (matched spread), (ii) ESMA external reviewer quality, (iii) §40B/§45Z access	0–1 index + (opt.) bp	Index = Issuance/stock (0/1) + ESMA reviewer (0/1) + §40B/§45Z (0/1) → (0–3)/3	t–1	(reduces cost impact)	EU (2025); OECD (2024); U.S. DOE (2025)	Within-index weights: Greenium 0.40, ESMA 0.35, §40B/§45Z 0.25. If no greenium, exclude from the index (do not assign 0).
DV	Emission intensity	gCO ₂ /pkm (or CO ₂ /ASK)	CO ₂ = 3.16 × fuel (kg); RPK great-circle; fuel by actually flown distance	t	—	ICAO (2025); EASA (2022)	The same distance definition must be used; units must be consistent.

Note: Expected signs indicate the direction on CO₂/RPK; “↓” denotes a decrease, “↑” an increase.

Source: Authors

4.2 Analysis design and protocol

The analysis followed a five-step protocol. First, we defined themes as Operations, Technology–SAF, Economics–Pricing, and Governance–MRV. Second, we mapped concepts to instruments and regimes (ReFuelEU → SAFAI; EU ETS/CBAM → CPP and RAI; MRV → MRVC; greenium/incentives → GFA). Third, we verified conformance with the Table 5 (T5) measurement and unit standards (e.g., CO₂/RPK, Net Effective Carbon Rate, SAF percentages). Fourth, we reported directional results with context and sources, reproducing any effect sizes only as stated in the original documents. Fifth, we triangulated by comparing conflicting findings across sources, noting discrepancies in the narrative and documenting them in Section 5. In parallel, we used the comparative policy matrix (T6) to place regimes side by side—Objective, Scope, Timeline, Compliance/Enforcement, and Expected directional effect—and discussed findings at the mechanism level.

4.3 Limitations and validity–reliability

This study relies on secondary sources; interpretation is directional and avoids causal claims. Metrics (CO₂/RPK, Net ECR) follow T5; definitional differences were footnoted and irreconcilable inconsistencies excluded. Validity and reliability were supported by multi-source verification, transparent reporting of contradictions, and a priori inclusion/exclusion criteria. Readers should consult the latest official versions of cited regulations and guidance.

5 FINDINGS

This section followed the concept–indicator framework defined in Section 4 via T5 (RAI, CPP, SAFAI, MRVC, GFA → CO₂/RPK) and the policy/mechanism comparison via the T6 matrix. No new data were produced, no effect-size estimation was conducted; only the elements explicitly reported by the official/semi-official documents **consulted** and peer-reviewed studies were conveyed directionally.

Table 6*(T6) Policy/Mechanism Matrix — aligned with T5 (simplified)*

Regime/Policy	Objective–Scope–Timeline (summary)	Compliance & MRV (summary)	T5 mapping	Expected directional effect	Sample evidence / Source
CORSIA (ICAO)	International flights; Pilot 2021–23, Phase 1 2024–26, Phase 2 2027–2035	Annex 16 Vol. IV; annual monitoring–verification–reporting and unit cancellation	RAI, MRVC	RAI↑ → CO ₂ /RPK↓; MRVC↑ → signal effect↑	(ICAO, 2023a; ICAO, 2025)
EUETS (aviation)	Intra-EU/EEA; gradual phase-out of free allocation from 2024+	EU MRR 2018/2066; 31 March report, ≥10 years of records	CPP, MRVC, (RAI)	CPP↑ → CO ₂ /RPK↓; MRVC↑ → effect↑	(EU, 2018; ICAO, 2024 SAF)
ReFuelEU (EU 2023/2405)	All flights departing the EU; SAF: 2% (2025) → 6% (2030) → 20% (2035) → 70% (2050); RFNBO sub-targets	90% uplift; EU Union Database; independent verification; Annex II reporting	SAFAI, (RAI), MRVC	SAFAI↑ → CO ₂ /RPK↓	(EU, 2023a Annex I–II; ICAO, 2025; ICAO, 2024 SAF)
CBAM (EU 2023/956; 2023/1773)	Imported steel/cement/aluminium, etc.; Transition 2023–25 reporting, 2026 certificates	Certificate price indexed to EUETS average; 31 May delivery; ≥80% quarter-end balance	(indirect CPP), (RAI)	CPP (indirect)↑ → CO ₂ /RPK↓	(EU, 2023b; EU, 2023c)
Financing/Incentives (GFA)	ESMA external reviewer framework; §40B/§45Z (US)	Greenium/issuance information; reviewer eligibility; access to tax credits	GFA → SAFAI	GFA↑ → SAFAI cost effect↓ → CO ₂ /RPK↓	(ESMA, 2025; OECD, 2024; U.S. DOE, 2025)
Operational measures (CDO/OPD, route/profile)	Approach/route optimization; ATM	Implementation/SOP; monitoring with flight data	Operations → DV	Operations ↑ → CO ₂ /RPK↓	(Aydoğan & Çetek, 2022; Tian <i>et al.</i> , 2019; Ryerson <i>et al.</i> , 2015; Şafak <i>et al.</i> , 2017; Şafak <i>et al.</i> , 2018)

Note: The “expected directional effect” column summarizes the direction on CO₂/RPK.

Source: Authors

5.1 Policy channels and mechanisms

eFuelEU's rising Sustainable Aviation Fuel (SAF) shares, RFNBO sub-targets, the 90% uplift rule, and EU-level verification/reporting increase SAFAI and MRVC, supporting SAFAI \uparrow \rightarrow CO₂/RPK \downarrow (EU, 2023a; ICAO, 2025; ICAO, 2024 SAF; EU, 2018). The revised EU ETS clarifies CPP (EU Allowance price \times coverage); higher CPP relates to lower CO₂/RPK, with strong MRV amplifying effects. CORSIA–EU ETS timeline/method gaps elevate dual-reporting costs (EU, 2018; ICAO, 2025). Operationally, CDO/OPD and route/profile optimization yield context-dependent reductions (\sim 3–6% to \sim 30–40%), complementing policy effects (Aydoğan & Çetek, 2022; Tian *et al.*, 2019; Ryerson *et al.*, 2015; Şafak *et al.*, 2017; Şafak *et al.*, 2018). Financing channels—green/SLB bonds (potential greenium), ESMA reviewer standards, and U.S. §40B/§45Z credits—can narrow near-term SAF premia and support SAFAI (OECD, 2024; ESMA, 2025; U.S. DOE, 2025). On governance and competitiveness, ReFuelEU applies from 2024/2025, while CBAM reports in 2023–2025 and imposes certificates from 2026, priced off the EU ETS weekly average with 31 May surrender and \geq 80% quarter-end balance rules (EU, 2023a; EU, 2023b; EU, 2023c). Overall, these mechanisms strengthen RAI/ CPP and are consistent with H1–H4 on intensity reduction and H5 on fragmentation-linked compliance costs.

5.2 Limits and transparency

Consistent with the triangulation protocol in Section 4.6, three recurring discrepancies across sources were identified. First, for ReFuelEU milestones, secondary summaries report only 2025/2030/2035/2050 (2/6/20/70%), whereas Regulation (EU) 2023/2405 and ICAO briefs also specify intermediate targets (e.g., 34% by 2040, 42% by 2045) and RFNBO sub-targets; Annex I is the authoritative schedule (EU, 2023a; ICAO, 2025). Second, reported savings from CDO/OPD and route/profile optimization vary 3–6% in constrained airspace versus 30–40% in favorable trials/models (Ryerson *et al.*, 2015; Aydoğan & Çetek, 2022; Şafak *et al.*, 2017; Şafak *et al.*, 2018; Tian *et al.*, 2019)—so we avoid cross-study averaging. Third, CBAM timing is often misstated: entry into force in 2023 with transitional reporting in 2023–2025, while certificates apply from 2026; CPP distinguishes reporting from obligation (EU, 2023b; EU, 2023c).

The findings are directional, and effect sizes are not estimated. CO₂/RPK and other metrics are used as reported in the sources, and studies with definitional inconsistencies are excluded. Because regulatory texts and guidance may be updated, readers should consult the most recent official versions when interpreting MRV requirements and timelines (EU, 2018; EU, 2023a; EU, 2023b; EU, 2023c; ICAO, 2025).

5.3 Synthesis and hypothesis alignment

Overall, the assembled evidence is directionally consistent with the T5 measurement standard and the T6 policy–mechanism matrix. Specifically, we find directional support for H1–H5: higher regime alignment (RAI) and effective carbon price exposure (CPP)—with stronger effects under greater MRV maturity (MRVC)—together with higher SAF adoption intensity (SAFAI) and operational optimization (CDO/OPD and route/profile), are associated with lower CO₂/RPK, whereas greater cross-regime fragmentation aligns with higher compliance burdens. By design, we do not estimate effect sizes or make causal claims; quantitative values are reproduced as reported under a common CO₂/RPK definition. For definitions, coding choices, and regime details, see T5 and T6.

6 DISCUSSION AND INTERPRETATION

6.1 Synthesis of findings: T5–T6–Cross-reading of the hypotheses

The findings indicate that, within multi-layered climate governance, the RAI–CPP–SAFAI triangle exerts a consistent downward pressure on CO₂/RPK when supported by MRVC and GFA. ReFuelEU Aviation’s phased minimum SAF shares together with the annual reporting/verification provisions (Annex I–II) systematically encourage technology substitution, thereby increasing SAFAI (EU, 2023a). The CPP signal is strengthened by the price × coverage dynamic in the EUETS and the CBAM’s certificate pricing indexed to the EUETS; in CBAM, the 31 May annual surrender and the quarter-end ≥80% minimum balance threshold determine the timing of the signal (EU, 2023b; EU, 2023c). The behavioural effect of this signal increases when MRV maturity is high; the verified reporting schedule, record-keeping, and data-gap rules under EU

MRR 2018/2066 define the institutional basis of this maturity (EU, 2018). The GFA channel softens the short-term SAF cost differential: ESMA’s standard on external reviewers improves information quality, sustainable/SLB issuances can provide a greenium under certain conditions, and §40B/§45Z incentives in the U.S. support production and adoption (ESMA, 2025; OECD, 2024; U.S. DOE, 2025). On the operations side, studies on CDO/OPD and route/profile optimization support the directional relationship with reported savings (Aydoğan & Çetek, 2022; Tian *et al.*, 2019; Ryerson *et al.*, 2015). In T5, RAI, CPP, SAFAI, MRVC, GFA, and DV (CO₂/RPK) are reduced to measurable indicators, while in T6 the ReFuelEU/ EUETS/CORSIA/CBAM rows comparatively present differences in objective–scope–timeline–compliance.

6.2 Theoretical contribution: policy mix in a “contested architecture”

The framework conceptualizes firm response along three axes: RAI (coordination of CORSIA– EUETS–ReFuelEU–CBAM), CPP (effective carbon price via EUETS and CBAM), and SAFAI (drop-in SAF and the RFNBO pathway). MRVC is positioned as a multiplier of this mix, heightening the behavioral force of the price signal. GFA increases the feasibility of the transition through the financing-cost channel (ICAO, 2025; EU, 2023a; ESMA, 2025; OECD, 2024). Thus, the “fragmented governance” debate in the literature is made concrete by linking it to measurable indicators in T5 and to a comparative regime architecture in T6.

6.3 Managerial and policy implications (directional; non-assertive)

At the policy level, ReFuelEU’s demand assurance (Annex I percentages) together with the Annex II reporting/verification templates provide an infrastructure that scales SAFAI. CBAM’s EUETS-indexed method and the 31 May surrender plus $\geq 80\%$ quarterly balance threshold indicate that the border price signal is being internalized (EU, 2023a; EU, 2023b; EU, 2023c). At the management level for airlines, the triad of Operations (OPD/CDO) + SAF (LTAs) + Finance (green/SLB, ESMA-compliant) appears directionally consistent. Preparing for ReFuelEU percentages with a multi-source SAF portfolio, automating the MRV data pipeline (EU MRR and CORSIA schedule), and

refining route planning through RAI/CPM mapping are assessed as rational steps (ICAO, 2025; EASA, 2022).

6.4 Role of DV and controls (transparency note)

In this study, the dependent variable is CO₂/RPK (CO₂/ASK where necessary). The definition and reporting method are presented as they appear in the source (ICAO, 2025). Controls (fleet age/composition, load factor, range, fuel price, hub structure, demand recovery) are noted only to the extent reported in the source; no claim of quantitative standardization is advanced (EASA, 2022).

6.5 Evidence moments (anchoring to document sentences)

ReFuelEU's minimum SAF percentages—2% (2025), 6% (2030), 20% (2035), 34% (2040), 42% (2045), and 70% (2050)—together with RFNBO sub-targets (e.g., 1.2% (2030), 5% (2035), 10% (2040), 15% (2045), 35% (2050)) concretize the SAFAI mechanism in T6; in the same text, tankering is restricted with a 90% uplift (EU, 2023a). The CBAM certificate price is indexed to the EUETS weekly closing average; the 31 May surrender and the quarter-end $\geq 80\%$ balance rule determine the intensity and timing of the signal (EU, 2023b; EU, 2023c). On the operations side, CDO/OPD and route/profile optimization have reported roughly 3–4% fuel savings in certain contexts; other studies have reported directionally similar reductions (Aydoğan & Çetek, 2022; Tian *et al.*, 2019; Ryerson *et al.*, 2015).

6.6 Validity, reliability, and limitations

This study does not produce new data and does not provide an effect-size estimate; it conveys measurements explicitly reported in documents. Since no singular and generalizable bps coefficient is provided for the greenium, GFA is kept directional (OECD, 2024; ESMA, 2025). Operational findings are context-specific; airspace and procedural differences can affect the savings range (Aydoğan & Çetek, 2022; Tian *et al.*, 2019). Since regime timelines and implementation rules can be updated through

secondary legislation/guidance, interpretations should be made based on the latest versions of the official texts (EU, 2018; EU, 2023c).

6.7 Robustness and future work

Critical claims are supported, where possible, by ≥ 2 independent sources (e.g., ReFuelEU + ICAO/SAF; EUETS/CBAM two-source triangulation). Even if the ReFuelEU percentages vary, the direction SAFAI \uparrow \rightarrow CO₂/RPK \downarrow holds; as MRVC increases, the CPP effect strengthens (ICAO, 2025; EU, 2023a). In the future, case comparisons using the T5 indicators and matched event studies (pre-/post-policy roll-out) can be conducted with accessible quantitative data.

7 CONCLUSION

Covering 2010–2025 with a semi-systematic synthesis of peer-reviewed and official sources, this study offers a decision-oriented framework that links multi-layered regimes to airline emissions intensity (CO₂/RPK) through five measurable channels under the Table 5 (T5) measurement standard. In doing so, it directly closes RQ1–RQ3 and remains directionally consistent with hypotheses H1–H5. The evidence indicates that stronger RAI, higher effective carbon prices (CPP), and scaled drop-in SAF adoption (SAFAI) are directionally associated with lower CO₂/RPK, with monitoring–reporting–verification maturity (MRVC) sharpening price-signal pass-through and access to green finance and targeted incentives (GFA) easing near-term SAF cost premia. Operational measures (CDO/OPD, route/profile optimization) provide complementary short-run gains, while timing/methodology mismatches across CORSIA–EUETS–ReFuelEU increase compliance burdens. Policy implications follow directly: harmonize MRV rules and implementation schedules, secure multi-source long-term SAF offtakes, automate MRV data pipelines, embed RAI/CPP mapping in network planning, and utilize green/SLB borrowing and applicable tax credits to bridge transition costs.

This assessment has clear limits: it relies on secondary evidence, reports directional rather than causal effects, and preserves source definitions and units. Future research should quantify the MRVC \times CPP interaction, trace the finance \rightarrow SAF \rightarrow CO₂/RPK pathway with firm-level data, test CBAM’s supply-chain cost

effects for airlines, and conduct matched pre/post policy analyses using the common T5 measurement standard. Within these bounds, the results support a practical conclusion: when regulation, markets, and operations are co-designed and supported by robust MRV and fit-for-purpose finance, durable reductions in airline CO₂/RPK are feasible and can be achieved without undermining competitive positioning.

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