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IMPACTS OF ITS ON AVIATION EFFICIENCY: PBN IMPLEMENTATION IN BRAZILIAN AIR ROUTES

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ABSTRACT

This study examines the impact of Intelligent Transportation Systems (ITS), focusing on Performance-Based Navigation (PBN), on the operational efficiency of Brazilian commercial aviation. Using ANAC microdata from the 14 busiest domestic routes between 2010 and 2024 (≈544,000 completed flights), we estimate the association between PBN adoption and flight time, fuel consumption, and CO_2 emissions. Multiple linear regression models with robust errors control for route distance and aircraft type, and a robustness specification applies log-transformed flight time with route fixed effects. Results indicate that higher PBN adoption is associated with average reductions of 2,6 minutes in flight time, 27,7 kilograms of fuel, and 87,6 kilograms of CO_2 per flight. While these per-flight effects are modest, their aggregation across high-frequency routes translates into substantial operational savings and avoided emissions. The findings highlight the strategic importance of ITS/PBN in enhancing efficiency, supporting sustainable air transport, and informing policies aimed at decarbonization in emerging economies.

Keywords: Intelligent Transportation Systems, Performance-Based Navigation, Brazilian Aviation, Air Traffic Management, Operational Efficiency.

GENERATIVE AI USAGE STATEMENT

The authors declare that the use of generative AI tools was restricted to technical support activities, without compromising the originality, analysis, and conclusions presented in the work. All information obtained through these resources was carefully evaluated and integrated into the study, ensuring methodological rigor and academic integrity. ChatGPT (OpenAI, Codex model) was used to assist in the revision and adjustment of Python code applied in the statistical modeling and data processing stages of the analysis.

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1 INTRODUCTION

Intelligent Transportation Systems (ITS) integrate automation, monitoring, and data analysis technologies to improve the performance and management of transport networks. In aviation, ITS applications such as Performance-Based Navigation (PBN) are strategically important to optimize airspace use, reduce flight distances, and lower fuel consumption, thereby contributing to both efficiency and sustainability goals (ICAO, 2009; Garg & Kaur, 2023).

The progressive implementation of PBN in Brazil, initiated in 2010, provides an opportunity to empirically assess its operational impacts using official microdata from ANAC. The dataset of the 14 busiest routes (2010–2024) enables measuring efficiency gains in time, fuel, and emissions.

Furthermore, ITS play a critical role in enhancing Air Traffic Management (ATM) by supporting Collaborative Decision Making (CDM) environments. According to ICAO (2005) and AASHTO (2021), ITS technologies contribute to a more predictable and efficient use of airspace by enabling real-time integration between surveillance systems, control nodes, and flight planning platforms. This integration optimizes slot allocation, minimizes delays, and strengthens the interoperability of CNS/ATM subsystems within performance-based frameworks.

In Brazil, PBN was gradually implemented across major Terminal Maneuvering Areas (TMAs), beginning in Recife (2010), followed by Rio de Janeiro (2011), and later expanding to São Paulo, Belo Horizonte, Brasília (2015), Salvador (2017), and finally Curitiba and Porto Alegre (2017) under the PBN-SUL project (DECEA, 2013; ICAO, 2011; ICAO, 2019) . This structured rollout allowed for the redesign of more direct routes, with tangible gains in flight time and emissions reduction.

Despite international evidence of PBN's efficiency gains, empirical assessments based on large-scale operational data remain limited in emerging economies. In this context, this study employs official ANAC microdata covering more than 500,000 flights across Brazil's 14 busiest domestic routes (2010–2024) to quantify the associations between PBN adoption and operational indicators such as flight time, fuel consumption, and CO_2 emissions.

The contribution of this research is threefold: to provide large-scale empirical evidence of PBN's impact in a developing aviation market, to apply robust statistical modeling with controls for distance and fleet heterogeneity, and to inform air transport policy and sustainability strategies in Brazil and other ICAO South America Region countries.

2 LITERATURE REVIEW

Performance-Based Navigation (PBN) represents a paradigm shift from prescribing specific navigation sensors or ground-based aids to specifying performance requirements (accuracy, integrity, continuity, functionality) for RNAV/RNP systems. In the case of RNP, on-board performance monitoring and alerting is also required. These concepts are consolidated in the ICAO Doc 9613 – PBN Manual, which standardized RNAV and RNP specifications globally (ICAO, 2012). ICAO (2005) defined ATM evolution toward trajectory-based operations, where PBN ensures predictable, time-compliant trajectories.

In the United States, PBN is a cornerstone of the NextGen modernization program. With high RNAV/RNP equipage rates in the fleet, the FAA implemented Metroplex redesigns, Optimized Profile Descents, and RNP AR procedures to reduce vectoring and track miles. The "Greener Skies" initiative at Seattle-Tacoma quantified average savings of ≈9 minutes and ≈87 gallons of fuel per

arrival, corresponding to about 1 ton of CO_2 avoided per flight, with projected systemwide annual reductions of millions of gallons of fuel (Alaska Airlines, 2015; FAA, 2022).

In Europe, Eurocontrol and SESAR combined mandates for RNAV (RNAV 1 in TMAs, RNAV 5 en-route) with the progressive deployment of Free Route Airspace (FRA) in the upper airspace. According to PRB/PRC studies, FRA reduced route extension relative to the great-circle distance, generating measurable fuel and CO_2 reductions, with projected savings in the order of millions of tonnes of fuel annually once full FRA coverage is achieved (EUROCONTROL, 2025a, 2025b; European Commission/PRB-PRC, 2025). Complementary initiatives include Continuous Descent/Climb Operations (CDO/CCO) and advanced RNP AR/RF procedures in complex terminal areas.

In the South American Region (SAM), ICAO and national ANSPs advanced PBN implementation through regional plans. In Brazil, the SIRIUS program led by DECEA redesigned RNAV routes, SIDs/STARs, and RNP approaches, improving flow predictability, reducing flight times and fuel consumption, and mitigating noise via accurate track keeping (CANSO, 2019). In 2024, ICAO reported that 92.4% of international runway ends in SAM had PBN approach procedures and 61.9% of SIDs/STARs were PBN-based (ICAO/GREPECAS, 2024). These advances align with Brazil's national CO_2 action plan, which uses ICAO methodology to quantify fuel and emission reductions (ANAC/ICAO, 2022, 2024).

The literature shows consensus that PBN shortens track miles, reduces level-offs and holding, and increases the repeatability of trajectories, especially in congested TMAs. RNAV SIDs/STARs and en-route FRA routes improve throughput and predictability, while reducing controller workload (EUROCONTROL, 2025a; FAA, 2022). In degraded weather conditions, vertically guided PBN approaches (e.g., LPV, RNP AR) reduce minima, go-arounds, and diversions, thereby lowering contingency fuel needs and improving operational reliability (ICAO, 2012; FAA, 2022).

Empirical studies complement institutional reports. For example, Pamplona et al. (2021) used fast-time simulations to compare conventional ILS with RNP approaches, reporting measurable reductions in fuel burn and flight time. Similarly, M'Azzuri et al. (2025) found that RNP procedures at an Indonesian airport cut fuel consumption by up to 15% in the approach phase compared to ILS. These findings confirm that PBN's efficiency benefits are observable in both simulation and real-world contexts across diverse operational environments.

Because fuel consumption is directly related to distance flown and vertical profile, PBN delivers proportional reductions in fuel burn and CO_2 emissions ($\approx$3.16 t CO_2 per tonne of fuel). Case studies such as Greener Skies and European FRA/CCO/CDO analyses report significant savings at both flight and systemwide levels (Alaska Airlines, 2015; EUROCONTROL, 2025a). In addition, accurate track keeping enables noise abatement by concentrating trajectories over less-sensitive areas, reducing population exposure (EUROCONTROL, 2025b; CANSO, 2019).

Importantly, PBN is recognized within ICAO's State Action Plans on Aviation CO_2 Emissions Reduction, serving as a fundamental operational measure to help countries meet climate targets. In Brazil, ANAC and DECEA explicitly highlight optimized RNAV and RNP routes as contributors to national emission mitigation strategies (ANAC/ICAO, 2022, 2024).

In addition to operational and environmental aspects, the literature emphasizes the human–machine interaction challenges associated with advanced avionics. Rondon et al. (2015) highlight that increasing levels of cockpit automation require pilots to adapt to new cognitive and procedural demands, which directly influence the safety and efficiency of PBN operations. This underscores that PBN benefits are not only technological, but also depend on how effectively flight crews integrate automated systems into decision-making.

Within the broader framework of Intelligent Transportation Systems (ITS) applied to aviation, PBN is a critical enabler of Trajectory-Based Operations (TBO), where each flight is managed in four dimensions (latitude, longitude, altitude, and time). In practice, TBO = PBN + Time-Based

Management (TBM), supported by Collaborative Decision Making (CDM) and SystemWide Information Management (SWIM) to share data across stakeholders in near-real time (FAA, 2022, 2024). By ensuring predictable lateral and vertical trajectories, PBN allows the ATM system to shift from tactical vectoring to strategic trajectory management, increasing efficiency and reducing uncertainty (ICAO, 2005; FAA, 2022).

More broadly, PBN is embedded within the expanding field of Intelligent Transportation Systems (ITS). A systematic review by Garg and Kaur (2023) synthesizes two decades of ITS research, showing how the Internet of Things (IoT), the Internet of Vehicles (IoV), and cooperative frameworks enhance predictability, safety, and sustainability across transport modes. In this study, we operationalize that perspective by estimating flight-level associations between PBN exposure and efficiency outcomes using multiple linear regression with robust errors and route fixed effects—an evaluation approach consistent with benefit-assessment frameworks for NextGen/PBN (Timar, Post, & Hunter, 2013). This reinforces that PBN is a critical ITS enabler, closely aligned with data-driven traffic management and multi-stakeholder collaboration.

Despite broad consensus on efficiency and sustainability benefits, there remain regional and methodological gaps. Large-scale empirical assessments outside North America and Europe are limited, and many early studies relied on fast-time simulations or case-specific before/after analyses. ICAO and regional groups have highlighted the need for data-driven analyses using operational microdata, robust econometric modeling, and systematic reporting of uncertainty (ICAO/GREPECAS, 2024; ANAC/ICAO, 2024). Brazil and the SAM Region, with diverse traffic corridors, remote areas, and heterogeneous infrastructure, provide a natural laboratory for measuring the association between PBN implementation and operational/environmental performance at scale.

3 METHODOLOGY

This study adopts a quantitative and empirical approach to assess the impact of Performance-Based Navigation (PBN) on operational indicators of Brazilian aviation. The analysis is based on Statistical Air Transport Data from ANAC, covering the 14 busiest domestic air routes between 2010 and 2024, which together accounted for over 1% of total regular passenger flights. Only completed commercial flights (landed/arrived) were considered (ANAC label: REALIZADO) (ANAC, 2025 – VRA), and aircraft models with at least 5% operational share on those routes were retained to ensure statistical robustness (Table 1 and Table 2).

Table 1: Domestic air routes in Brazil with more than 1% share (ANAC, 2025)

Air Route	Takeoffs	Share (%)	Distance (NM)
SBSP/SBRJ	535,958	4,42%	197,44
SBSP/SBBR	234,448	1,93%	471,03
SBSP/SBCF	207,596	1,71%	283,13
SBPA/SBGR	200,599	1,65%	467,38
SBSV/SBGR	188,179	1,55%	784,1
SBRF/SBGR	180,994	1,49%	1134,38
SBSP/SBPA	174,044	1,44%	452,36
SBSP/SBCT	173,911	1,43%	178,92
SBGR/SBCT	161,735	1,33%	194,03
SBGR/SBCF	160,245	1,32%	268,07
SBGR/SBBR	158,770	1,31%	461,45
SBRJ/SBBR	153,101	1,26%	501,03
SBGR/SBGL	149,357	1,23%	181,85

SBGR/SBFZ	131,088	1,08%	1267,09

Table 2: Aircraft models with more than 5% share on selected routes

Aircraft Model	Operations	Share (%)
B738	388,77	26,74
A320	345,761	23,78
A319	241,855	16,63
B737	124,93	8,59
A321	89,473	6,15

To estimate the influence of PBN on actual flight time, fuel consumption, and CO_2 emissions, we employed a multiple linear regression model (Eq. 1) structured as:

$$Y_{it} = \beta_0 + \beta_1 PBN_{it} + \beta_2 Distance_{it} + \sum_{j=1}^{m} \beta_{j+2} AircraftModel_{jit} + \varepsilon_{it} \text{ (Eq. 1)}$$

Where Y_{it} represents the dependent variable (flight time, fuel burn, or CO_2 emissions); PBN_{it} is the degree of PBN implementation; $Distance_{it}$ is the planned route distance (in nautical miles); and $AircraftModel_{jit}$ are dummy variables for each aircraft type (A320, A319, A321, B737, B738). The error term ε_{it} captures unobserved heterogeneity.

For each flight i on date t we computed a flight-level PBN exposure index PBN_{it} as the mean of the origin and destination TMA indices on that date:

$$PBN_{it} = \frac{1}{2}\left(PBN_t^{orig} + PBN_t^{dest}\right).$$

Each airport-level index $PBN_t^a \in [0, 1]$ is built from the documented exact implementation date of PBN at airport a (when available) and evolves linearly from 0 to 1 between that start date and 31 Dec 2024 (analysis window end). Formally, for airport a with start date S_a,

$$PBN_t^a = \begin{cases} 0, & t < S_a \text{ or } S_a \text{ not documented (None)} \\ min\left(1, \dfrac{t - S_a}{(2024 - 12 - 31) - s_a}\right), & t \geq s_a \end{cases} (\text{rounded to two decimals}).$$

When an airport's PBN implementation date is undocumented, the airport-level index is set to 0 throughout the analysis window. This conservative rule avoids unverifiable back-dating of PBN exposure and ensures that results are not biased by missing records. In practice, airports with no recorded deployment remain at zero, while those with documented start dates evolve linearly toward full implementation by 2024.

Robust standard errors (HC3) were used to address heteroskedasticity and residual non-normality, as identified by the Breusch-Pagan and D'Agostino-Pearson tests, respectively. This ensures consistent inference despite potential violations of classical linear regression assumptions.

To improve robustness for flight-time modeling, we removed speed outliers using route-specific bounds. We computed block speed (NM/h) and, for each route, defined robust envelopes from quantiles and IQR with physical guard-rails (120–520 kt). Observations outside the route envelope were excluded. This reduces leverage from timestamp errors and atypical operations.

Finally, CO_2 emissions were estimated following the ICAO methodology for commercial aviation, which applies a standard conversion factor of 3.16 to translate fuel burn into CO_2 emissions (ICAO, 2024). In our implementation, emissions were computed at the flight level as:

$$CO2_{fligh} = Fuel_{burn} \times 3.16$$

Where:

- $Fuel_{burn}$ = Total fuel consumption for the flight segment (kg);
- 3.16 = Conversion factor (1 ton of fuel produces 3.16 tons of CO_2);

This approach yields total CO_2 emissions per flight, consistent with system-level operational impacts. It is important to note that the ICAO Carbon Emissions Calculator typically expresses results per passenger, according to:

$$CO2_{pax} = \frac{(Fuel_{burn} \times 3.16) \times PaxLoadFactor}{TotalSeats}$$

Where:

- $PaxLoadFactor$ = Average global passenger load factor according to *Industry Statistics – Fact Sheet*, IATA (2016; 2019; 2025);
- $TotalSeats$ = Total number of available seats on the flight according to ANAC (2025).

The complete workflow for downloading and processing these data including route filtering, aircraft classification, construction of operational variables, and regression modeling is publicly documented in a GitHub repository at: https://github.com/olegantonov/ITS_DATA_ARTICLE_V3.

4 RESULTS

The analyzed dataset comprises 544,032 completed commercial flights recorded between 2010 and 2024, corresponding to the 14 most frequently operated domestic air routes in Brazil.

Table 3: Descriptive Statistics of Key Operational Variables

Variable	Mean	Standard Deviation	Minimum	Maximum
Actual Flight Time (min)	102,7	45,1	49	286
Fuel Consumption (kg)	4600,1	2196,1	2313,3	10832,1
CO_2 Emissions (kg)	14538,8	6939,7	7310,2	34229,6
Route Distance (NM)	480,4	326,8	178,9	1267,1
PBN Implementation *Index*	0,340	0,334	0	1
Average Speed (Knots)	257,4	64,2	121,2	398

Table 3 summarizes the variables; variability reflects route length and fleet heterogeneity.

4.1 REGRESSION RESULTS

To investigate the impact of PBN on operational efficiency, three multiple linear regression models were estimated each targeting one dependent variable: flight time, fuel consumption, and CO_2 emissions.

Table 4: Estimated Coefficients for Each Variable in the Three Regression Models

Variable	Coefficient – Flight Time (min)	*p*-value Flight Time	Coefficient – Fuel Consumption (kg)	*p*-value Fuel	Coefficient – CO_2 Emissions (kg)	*p*-value CO_2
Intercept	36,32	$p = 1\times10^{-30}$	226,11	$p = 1\times10^{-30}$	714,52	$p = 1\times10^{-30}$
PBN	–2,60	$p = 1\times10^{-30}$	–27,74	$p = 3{,}3\times10^{-8}$	–87,66	$p = 1\times10^{-15}$

Route Distance (NM)	0,137	$p = 1\times10^{-30}$	6,34	$p = 1\times10^{-30}$	20,05	$p = 1\times10^{-30}$
A320 (ref.)	-	-	-	-	-	-
A319	1,69	$p = 1\times10^{-30}$	-48,73	$p = 1\times10^{-30}$	-153,98	$p = 1\times10^{-30}$
A321	0,67	$p = 1\times10^{-30}$	1099,77	$p = 1\times10^{-30}$	3475,30	$p = 1\times10^{-30}$
B737	2,03	$p = 1\times10^{-30}$	201,44	$p = 1\times10^{-30}$	636,55	$p = 1\times10^{-30}$
B738	2,68	$p = 1\times10^{-30}$	254,02	$p = 1\times10^{-30}$	802,71	$p = 1\times10^{-30}$
R^2	0,964	-	0,993	-	0,993	-
N (flights)	544,032	-	544,032	-	544,032	-

Model fit is high for fuel and CO_2 ($R^2 \approx 0,993$) and strong for flight time after outlier removal ($R^2 \approx 0,964$). A robustness check with log (time) and route fixed effects yields $R^2 \approx 0,959$, with the PBN coefficient becoming statistically insignificant for time.

Interpretation caveat. Coefficients represent conditional associations given model fit and covariates. Magnitudes are most reliable for relative comparisons and for sample-level aggregation; they should not be generalized as structural causal effects, particularly for flight time, where route heterogeneity remains significant.

4.2 IMPACT OF PBN IMPLEMENTATION ON OPERATIONAL INDICATORS

The results confirm that greater adoption of PBN is statistically and operationally associated with gains in efficiency across all evaluated indicators.

For flight time, the coefficient for the PBN variable was –2,60 minutes ($p = 1\times10^{-30}$), indicating that higher levels of PBN adoption are associated with shorter block times, even after controlling for distance and aircraft type. While this effect is modest in magnitude, the model achieves a high explanatory power ($R^2 = 0,964$). Robustness checks using a log-transformed specification with fixed effects by route show that the PBN coefficient becomes statistically insignificant ($p \approx 0,082$), suggesting that time savings are heterogeneous across corridors and not uniformly observed, underscoring the importance of route-specific factors.

In terms of fuel consumption, the model estimated a reduction of –27,7 kg per flight per unit increase in the PBN index ($p = 1\times10^{-30}$). Although this represents only about 0,6% of the average fuel load, the aggregate effect across more than half a million operations is substantial, confirming the contribution of optimized trajectories to fuel efficiency. Distance remained the most influential variable (+6,34 kg per NM), as expected.

For CO_2 emissions, the model identified a reduction of –87,6 kg per flight per unit increase in PBN ($p = 1\times10^{-30}$), corresponding again to ≈ –0,6% of average emissions. Emissions rose proportionally with route distance (+20,05 kg per NM) and were strongly correlated with fuel burn. Aircraft such as the A321 and B738 exhibited the highest absolute consumption and emissions, reflecting their greater weight and seating capacity. While per-flight reductions are ≈0,6% of the averages, scaling by high-frequency corridors yields material system-level savings over hundreds of thousands of operations per year; we therefore emphasize aggregated and route-level perspectives in addition to per-flight effects.

Beyond the direct performance benefits of PBN, the integration of ITS into ATM systems supports coordinated airspace usage and improved situational awareness. This is enabled by data fusion, automated flow control, and systemwide information management (SWIM), as described in ICAO (2005). These pillars are critical for the advancement of trajectory-based operations (TBO) and reinforce long-term CNS/ATM interoperability goals outlined by ICAO.

5 CONCLUSIONS

This study provides empirical evidence that the implementation of Performance-Based Navigation (PBN) in Brazilian air routes is associated with measurable improvements in operational efficiency. The regression analysis indicates that, on average, PBN adoption reduces fuel burn by –27,7 kg (≈ –0,63%) and CO_2 emissions by –87,6 kg (≈ –0,63%) per flight, with models exhibiting a high explanatory power ($R^2 \approx 0,99$). For flight time, we observe a moderate reduction of –2,6 minutes in the OLS specification; however, when controlling for route heterogeneity through a log-transformed model with fixed effects, the coefficient loses statistical significance. This result suggests that time savings from PBN are not uniform but vary substantially across corridors.

Although per-flight reductions appear modest, their system-level impact is operationally and environmentally meaningful when scaled across high-frequency routes, with aggregate fuel savings in the order of tens of thousands of tons and avoided emissions exceeding 48,000 tons of CO_2. Such outcomes translate into both cost savings for airlines and progress toward broader sustainability objectives.

From a strategic perspective, the integration of PBN within the framework of ITS enhances the capacity of ATM to allocate airspace more predictably and efficiently. This supports the interoperability of CNS/ATM subsystems and strengthens the transition toward TBO recommended by ICAO.

Nevertheless, methodological limitations must be acknowledged. CO_2 emissions were estimated from average fuel burn using a fixed conversion factor, without disaggregation by flight phase or aircraft-specific engine performance. In addition, while the models account for distance and fleet composition, they remain sensitive to operational factors such as congestion, weather, and airline procedures.

Additionally, treating undocumented PBN dates as zero may understate exposure in isolated cases where documentation gaps exist. This conservative assumption, however, provides transparency and avoids inflating estimated benefits.

Future research should incorporate real-time flight performance data to enable finer-grained modeling of fuel use and emissions by phase of flight and aircraft type. The development of operational dashboards integrated with SWIM could further strengthen predictive analytics in air traffic control. These advancements are essential to validate and extend the findings presented here and to inform evidence-based policies aimed at decarbonizing air transport in emerging economies.

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