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EVALUATING THE IMPACTS OF MULTI-SCALE FLIGHT TRAJECTORY INEFFICIENCIES ON FUEL BURN FOR THE MAJOR BRAZILIAN ROUTES

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ABSTRACT

The aviation sector's urgent need to minimize fuel inefficiencies and CO2 emissions is underscored by the fact that non optimal air traffic management practices such as extended routing, suboptimal traffic sequencing and vectoring delays lead to significant additional fuel burn, cost increases and heightened environmental impact. To address these challenges, we created a framework to calculate ICAO Global Air Navigation Plan (GANP) indicator for additional fuel burn, which quantifies the excess fuel consumed beyond an ideal trajectory by converting time, distance and climb and descent inefficiencies into a unified metric. Our framework integrates radar track data, flight payload information and meteorological conditions to calculate each flight's excess fuel consumption and attribute this waste to different causes. An analysis of the 20 busiest domestic routes reveals that en-route extensions dominate additional fuel burn, particularly in long haul sectors subject to multi sector handovers and variable weather. In contrast, shorter city pair routes such as São Paulo to Rio de Janeiro exhibit higher temporal inefficiencies driven by vectoring and holding penalties. Seasonal peaks in January 2024 and February 2024 intensify both en-route and terminal area inefficiencies in key routes like Campinas/São Paulo (SBKP) and Salvador (SBSV) to Congonhas/São Paulo (SBSP), respectively. Our findings identify Curitiba (SBCT) to SBSP, SBCT to São Paulo/Guarulhos (SBGR) and Confins/Belo Horizonte (SBCF) to SBSP as the most fuel inefficient corridors, while the mature Santos Dumont/Rio de Janeiro (SBRJ) to SBSP flow demonstrates comparatively low variability. These insights offer Brazilian regulators quantitative evidence to prioritize airspace redesign and controller training. Targeted optimization of flight trajectories and refined terminal area procedures during peak traffic periods promise both environmental benefits and cost savings.

Keywords: Key Performance Indicators, Fuel Burn, Air Traffic Management.

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GENERATIVE AI USAGE STATEMENT

This research did not use generative AI.

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1 INTRODUCTION

The aviation sector must urgently reduce fuel waste and CO_2 emissions. Airlines burn additional fuel when controllers assign longer routes, sequence traffic inefficiently, or vector aircraft into delays (ICAO, 2024). Such inefficiencies increase costs, strain operators, and amplify climate impacts. To reach net-zero targets by 2050, experts estimate that 271 million tonnes of CO_2 reductions are required from aviation alone (EUROCONTROL, 2021).

A key instrument in this effort is ICAO's Performance-Based Approach (PBA) to Air Traffic Management (ATM), which introduces Key Performance Indicators (KPIs) to quantify operational efficiency. Among these, the KPI on additional fuel burn is particularly relevant, as it converts en-route and terminal inefficiencies into measurable environmental and economic costs (ICAO, 2022).

While prior studies have quantified fuel penalties from level-offs, holdings, or path extensions in international contexts, there remains limited empirical evidence for South American operations, especially under high-density airspace such as Brazil's. This paper contributes by applying a KPI-based framework that merges radar trajectories, payload data, and meteorological information to quantify excess fuel burn across the country's busiest routes. By linking extra consumption to specific causes, such as route extensions, holding patterns, and weather-driven deviations, the study fills a gap in the literature and provides a benchmark for analyzing operational efficiency in Brazilian airspace.

Our findings not only identify which airports and routes concentrate the highest inefficiencies but also demonstrate the value of integrating empirical data into ATM decision-making. The results offer regulators evidence to prioritize airspace redesign and controller training, showing how data-driven methodologies can both support environmental goals and generate economic gains for the aviation sector.

2 LITERATURE REVIEW

Fuel represents one of the largest and most volatile components of airline operating costs, accounting for roughly 28% of expenses for a typical A320 operator in 2003 and projected to exceed 45% shortly (Airbus, 2004, 2008). Beyond its economic impact, fuel burn directly drives CO_2 emissions, making efficiency in flight operations a critical goal for both cost containment and environmental stewardship (Henderson et al., 2012; Green, 2009). To reduce unnecessary consumption, airlines employ advanced planning tools to optimize fuel loads and cruising profiles (Chang et al., 2014), while weight management, airport design, and dynamic surface traffic management help trim idle taxi times and cut emissions on the ground (Simaiakis et al., 2014).

Once airborne, inefficiencies in routing and sequencing accumulate additional burn. Adaptive rerouting and improved sector coordination can limit deviations during cruise, whereas descent procedures in terminal areas remain highly sensitive to vectoring, holdings, and level-offs. Continuous descent operations and refined protocols have shown promise in mitigating low-altitude inefficiencies (Ryerson et al., 2014; Salah, 2014), yet empirical work demonstrates that level-offs and path stretches still impose significant fuel penalties (Szenczuk e Eller, 2022). Infrastructure and ATM modernization further contribute to efficiency, with flexible airspace use, redesigned routes, and reduced separation minima enabling more direct trajectories, while congestion management at major hubs helps avoid airborne and ground delays (Simaiakis et al., 2014; Reynolds, 2014).

Recent studies highlight the influence of contextual factors such as traffic intensity, weather, and national airspace structure, with evidence from Brazilian commercial aviation showing marked variations in fuel use and flight times across different operating conditions (Szenczuk et al., 2025). Despite extensive literature on operational efficiency, most research has focused on global frameworks (e.g., ICAO standards) or European and North American case studies, leaving South American contexts underexplored. This study addresses that gap by presenting a methodology to calculate additional fuel burn based on ICAO guidelines, applied to Brazilian airspace. In doing so, it builds on international findings while extending the literature through route-specific analysis and a focus on both en-route and terminal inefficiencies, providing actionable insights for operational improvements.

3 METHODOLOGY

The additional fuel burn indicator, as recommended in GANP by (ICAO, 2024) and in MCA 100-22 by (DECEA, 2020), is based on converting the flight time/distance and vertical inefficiency KPIs into an estimate of fuel burn, enabling the estimation of additional fuel consumption attributable to ATM. We calculated this indicator for the top 20 busiest routes and top 10 airports in the year 2024. The analysis covers the period from January 2023 to July 2024.

The indicator was developed from four KPIs to estimate additional fuel consumption caused by en-route inefficiencies, additional time in terminal areas, and level-offs during climb and descent. It captures horizontal, temporal, and vertical inefficiencies in flight operations. Additional fuel burn was calculated by: (i) multiplying excess distance by average en-route fuel rate; (ii) multiplying additional terminal time by average terminal fuel rate; and (iii) comparing actual versus ideal trajectories without level-offs during climb/descent. Terminal areas were modeled as 40 NM (or 100 NM) radius cylinders around airports, and reference conditions were defined by aircraft type, arrival heading, and entry sector.

We then use these indicators to calculate the additional fuel burn. An advanced version of the indicator was developed, with the calculation based on inefficiency and fuel consumption values computed for individual flights.

To estimate fuel consumption for each flight phase, the open aircraft performance model OpenAP (Sun et al., 2020) and meteorological data from the ERA5 reanalysis by the ECMWF ECMWF (2024) were used, with ERA5 data accessed via the FastMeteo Python package Sun e Roosenbrand (2023). OpenAP computes fuel burn using aircraft-specific performance curves and variables such as weight, altitude, true airspeed (TAS), and vertical rate. FastMeteo interpolates wind components (u, v) along flight trajectories, enabling accurate TAS calculation and, consequently, more precise estimation of point-by-point fuel consumption using OpenAP.

The KPI calculation was based on four data sources: Brazil's National Civil Aviation Agency (ANAC) flight microdata (e.g., fuel consumed, payload), actual flight trajectories from FlightRadar24 (FR24), ERA5 meteorological data, and ATM performance efficiency indicators.

With the interpolated wind components (u, v), the TAS was calculated at each point along the trajectory. This calculation used sequential differences in geographic coordinates to determine the heading angle relative to true north, enabling conversion of ground speed to TAS via vector subtraction of wind.

Using TAS, OpenAP can estimate the fuel flow at each point of the trajectory. First, the initial aircraft mass was estimated based on the operational empty weight from OpenAP, payload, and fuel consumed (from the microdata), plus operational margins, including fuel for an alternate aerodrome (assumed 60 minutes), 45 minutes of regulatory reserve, and 10% of total trip fuel as contingency.

Fuel flow (kg/s) at each trajectory point was estimated with OpenAP, which takes current aircraft mass, TAS, altitude, and vertical speed as inputs. At each time step, the computed fuel burn was subtracted from the aircraft's mass, updating its residual weight.

Next, the additional fuel consumption associated with each type of flight inefficiency was estimated. The final additional fuel burn value was obtained by summing the four components described above. The indicator was stored and structured by flight, allowing aggregation by period (day, month, year), aircraft type, airline, route, or airspace region.

4 RESULTS

Figure 1 presents the additional fuel consumption in kg/flight for each type of inefficiency on the top 20 routes.

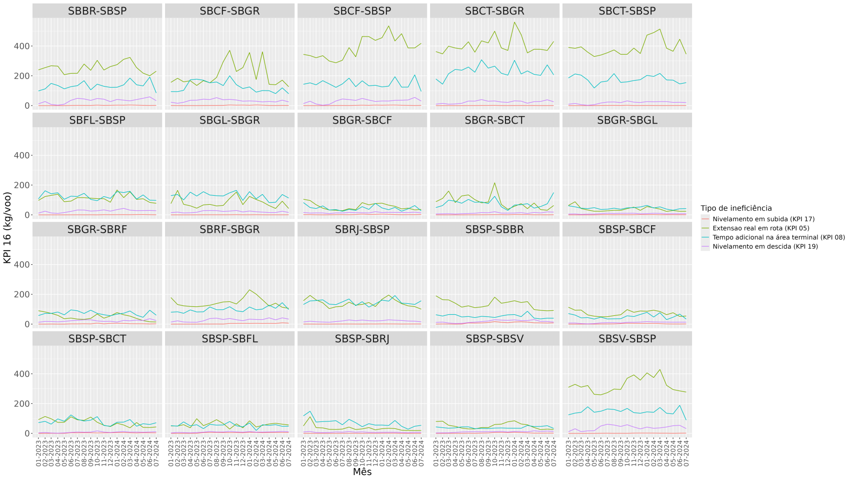


Figure 1: Temporal evolution of the average additional fuel consumption by type of inefficiency for the 20 busiest routes.

For the calculation of additional fuel consumption for both actual en-route extension and temporal efficiency in the terminal area, variant 1 was used (i.e., 40 NM for both departure and arrival terminal areas, and 40 NM for the ASMA). The temporal analysis reveals patterns that highlight the operational complexities of each flight phase. It is observed that the additional fuel consumption due to route extension inefficiencies and additional time in the terminal area show similar trends for most analyzed routes, with higher values compared to inefficiencies during the climb or level-off during descent.

Figures 2 display the percentage distribution of additional fuel consumption for each route between January 2023 and July 2024.

For the vast majority of routes, the inefficiency that accounts for the largest share of additional fuel burn is en-route extension. In turn, additional time in the terminal area represents slightly higher consumption for seven routes. Congonhas/São Paulo-Santos Dumont/Rio de Janeiro (SBSP-SBRJ) route has a relatively higher share of additional

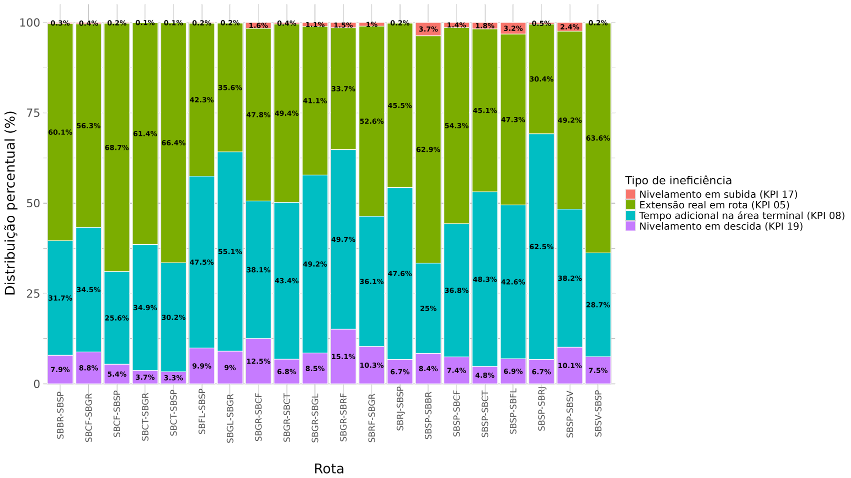


Figure 2: Percentage distribution of average additional fuel consumption by type of inefficiency and route.

time (62.5%) compared to en-route extension (30.4%). Others show very close proportions, such as São Pualo/Congonhas-Curitiba (SBSP-SBCT) (KPI08: 48.3%, KPI05: 45.1%). This is justified because the cruise phase, where en-route inefficiencies occur, represents the majority of the flight and thus contributes more to additional fuel burn. In very short routes like Rio de Janeiro–São Paulo, the complexity of the terminal phase contributes more to inefficient additional consumption due to limited room for deviation in cruise.

This behavior reflects the operational nature of the phases where these inefficiencies occur, with temporal efficiency in terminal area contributing significantly to the overall indicator. Certain routes, such as Confins-Congonhas/São Paulo (SBCF-SBSP) and Congonhas/São Pualo-Brasília (SBSP-SBBR), show higher cruise phase consumption than in the terminal area. This suggests a predominance of horizontal inefficiency over temporal inefficiency, possibly due to route restrictions, adverse weather, or airspace structure limitations forcing deviations from optimal trajectories. A worse performance is observed on the Salvador-Congonhas/São Paulo (SBSV–SBSP) leg compared to its inverse SBSP–SBSV. Specifically, the SBSV–SBSP route showed a higher incidence of flights with significant en-route extensions, indicating greater operational inefficiency.

The analysis in Figure 3 provides further insight.

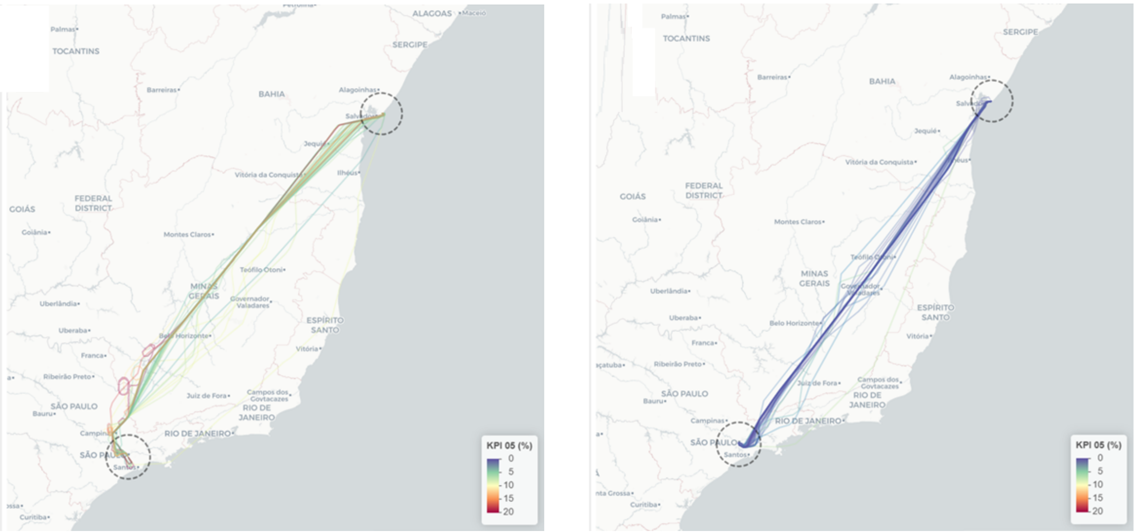
February is an atypical month, with higher traffic due to vacation season and Salvador's carnival, a major tourism driver that increases outbound flights from São Paulo. Holding patterns are observed near São Paulo on SBSV–SBSP flights, while no such occurrences were noted on the reverse route on the same day. Note that departures to the west from Salvador are not as direct as arrivals from the southwest, due to specific procedures for that airport. Thus, en-route extension is greater in one direction, increasing additional fuel burn in that flight phase.

Additionally, the data show that fuel burn in level segments is higher during descent. This is due to greater operational complexity and vectoring procedures implemented within the terminal area.

Figure 4 illustrates the evolution of additional fuel consumption considering all flight phases.

The time series analysis shows that routes tend to maintain stable consumption patterns, reflecting consistent operational procedures and traffic conditions.

The routes with the highest additional fuel consumption involve airports within the



(a) SBSV–SBSP.

(b) SBSP–SBSV.

Figure 3: En-route extension on reciprocal routes.

São Paulo Terminal Manouvering Area (TMA), the most complex traffic region in the country. Notably, routes SBCT-SBSP, Curitiba-Guarulhos/São Paulo (SBCT-SBGR), and SBCF-SBSP stand out. This pattern suggests the influence of seasonal factors, such as Brazil's summer, with higher air traffic demand and persistent convective weather, which leads to airspace congestion.

SBRJ-SBSP, the busiest route of the year, showed an upward trend in additional fuel consumption during the summer of 2024, peaking in February. The observed seasonality reflects the impact of weather and demand variation on operational efficiency.

With regard to vertical efficiency during climb and descent, the fuel consumption in kg/flight is calculated proportionally to the effective percentage within the respective flight phase, specifically considering the distance of level segments during climb or descent phases, multiplied by the average additional consumption.

Figure 5 presents the analysis of fuel consumption during the arrival and departure phases.

Seasonal peaks are clearly observed at airports in São Paulo, while the others show little variability during the period. The temporal continuity observed in the departure phase demonstrates stability in operational patterns, with minimal variations suggesting consistency in air traffic control procedures. The difference between the two phases highlights the greater operational complexity inherent in approach and landing procedures, where factors such as extended vectoring and holding patterns contribute to increased fuel consumption at low altitudes.

Particularly at airports with high traffic, vectoring procedures result in non-optimal trajectories. A peak in inefficiency is observed in January and February 2024 at Campinas/São Paulo (SBKP). The analysis in Figure 6 provides visual evidence of the seasonal impact within the terminal area.

Arrival traffic visualization within 40 NM of SBKP shows multiple simultaneous holding patterns in January, while in July 2023, traffic was more orderly with no observed holding procedures.

Figure 7 presents a ranking of the 20 busiest routes ordered by average additional fuel consumption (kg/flight). The most inefficient routes are SBCT-SBGR, SBCF-SBSP, and

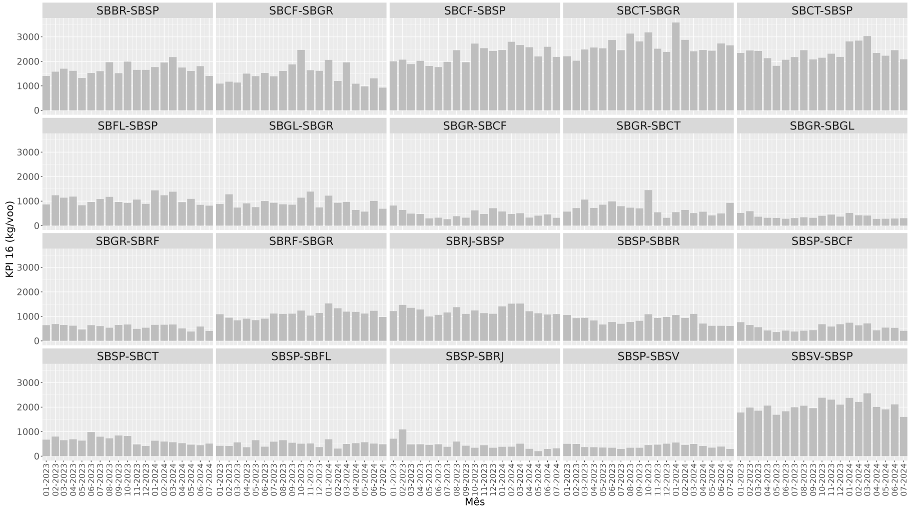
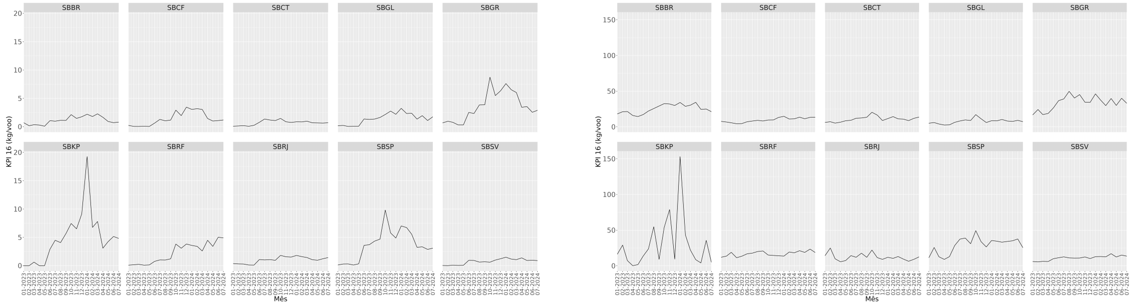


Figure 4: Temporal evolution of average additional fuel consumption aggregated by route.



(a) Departures (level-offs during climb). **(b)** Arrivals (level-offs during descent).

Figure 5: Temporal evolution of average additional fuel consumption due to level-offs in departure and arrival phases.

SBCT-SBSP. Their operational characteristics lead to higher average fuel consumption.

Flights departing from SBCT toward the São Paulo TMA exhibit higher horizontal inefficiency. This inefficiency is related to airspace structure limitations and traffic separation procedures needed to integrate Curitiba, originating flows into the São Paulo multi-airport system.

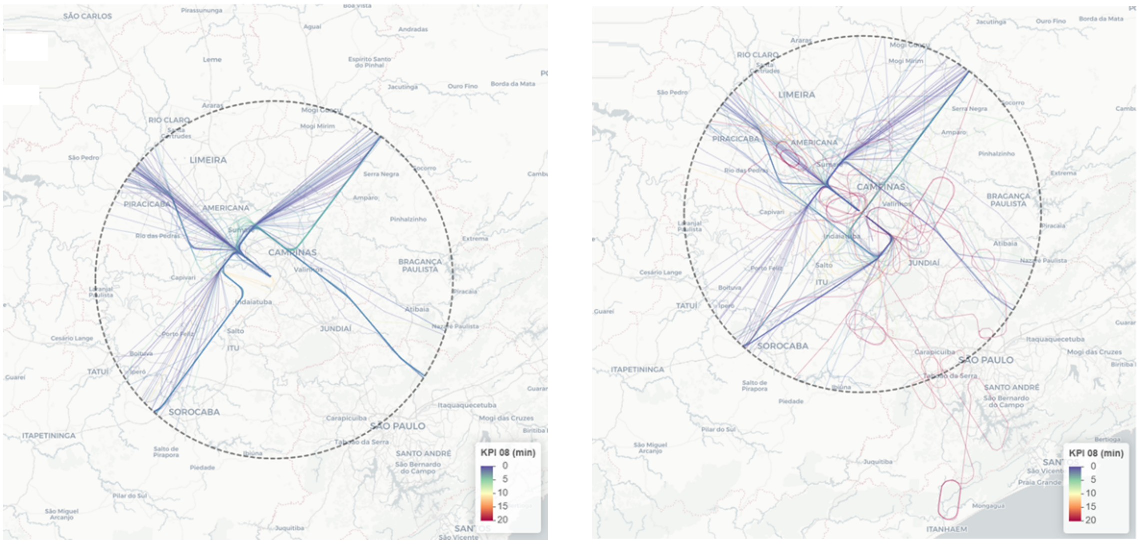
Confins-Congonhas/São Paulo (SBCF-SBSP) route also shows high inefficiency, mainly due to complex vectoring during approach into SBSP, resulting in increased fuel consumption.

It is worth noting that the most heavily trafficked route ranked as the second most efficient. This result can be attributed to its short distance, which minimizes the cruise phase (where fuel burn is highest), and optimized operational procedures due to high flight frequency.

Long-haul routes such as Salvador–Congonhas (SBSV-SBSP) and SBBR-SBSP show greater inefficiency as expected, due to longer cruise phases and additional complexities in managing traffic across multiple control sectors.

Figure 8 presents boxplots for the 20 analyzed routes, with 2% of outliers removed for better visualization.

Dispersion analysis confirms expectations, with greater variability on the SBCT–São



(a) July 8, 2023. **(b)** January 8, 2024.

Figure 6: Additional time in the SBKP terminal area.

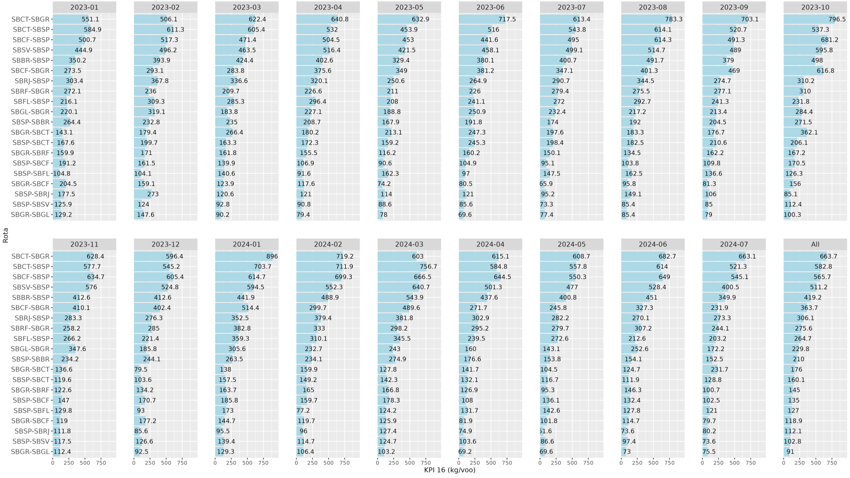


Figure 7: Ranking of average additional fuel consumption for the 20 busiest routes.

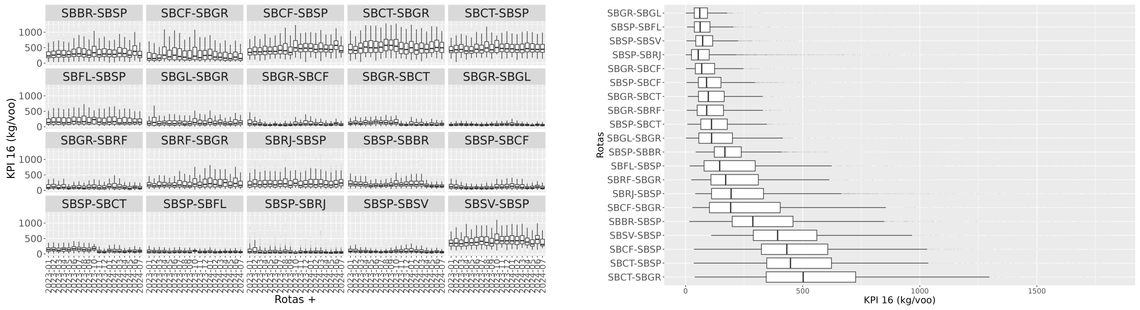
Paulo routes. Only SBCT-SBGR has a median above 500 kg/flight, standing out as the least energy-efficient route.

Quartile and range analysis provides further insights into operational consistency by route. Routes with less dispersion indicate greater predictability and more standardized procedures. The visualization confirms that longer routes such as SBBR–SBSP and both SBCT–SBGR and SBCT–SBSP show greater dispersion in consumption values.

The greater variability in long routes is due to increased exposure to meteorological variations along the trajectory and the complexity of managing traffic across multiple control sectors.

5 CONCLUSIONS

Based on the analysis of additional fuel burn across the 20 busiest Brazilian routes, horizontal en-route extensions consistently account for the largest share of additional fuel burn,



(a) Monthly dispersion by route. **(b)** Overall dispersion by route.

Figure 8: Dispersion analysis of additional fuel burn by route.

reflecting the dominant contribution of cruise phase inefficiencies to total extra consumption. Temporal inefficiencies in the terminal area, however, become more pronounced on shorter city-pair legs, most notably the São Paulo–Rio de Janeiro sector, where limited room for cruise deviations shifts the imbalance toward vectoring- and holding-driven fuel penalties.

Seasonal patterns emerge clearly: February 2024's elevated traffic corresponds to significant en-route extensions on the SBSV–SBSP leg. Peak inefficiencies in SBKP terminal operations during January and February underscore the increase in holding patterns due to high demand and weather conditions in summer. Routes traversing the São Paulo TMA, incur the highest average additional fuel consumption. In contrast, the country's busiest connection (SBRJ–SBSP) maintains low inefficiency levels thanks to its short distance and mature operational procedures.

Variability analysis further highlights operational consistency: long-haul sectors such as SBBR–SBSP and both Curitiba–São Paulo legs exhibit wider dispersion in per-flight fuel penalties, driven by extended cruise exposure to meteorological variability and multi-sector control handovers. Urban-proximity routes with standardized flows show tighter interquartile ranges, indicating more predictable performance.

By lowering national fuel consumption through en-route trajectory optimization and enhancing TMA procedures during high-peak demand periods, it is possible to strengthen both operational performance and environmental sustainability. In line with the literature, these findings reinforce the role of advanced air traffic management strategies in mitigating inefficiencies, while also pointing to the potential of benchmarking against international best practices. Future research could benefit from referencing established methodologies, such as Continuous Descent Operations (CDO), Performance-Based Navigation (PBN), or Free Route Airspace (FRA), as applied in regions like Europe and North America, to explore how similar approaches might be adapted to the Brazilian context and improve trajectory optimization within complex TMAs.

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