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Vertical Efficiency Analysis of Continuous Climb and Descent Operations in Canadian Terminal Areas

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Abstract

This work presents a data-driven framework that links ADS-B surveillance data with ICAO GANP vertical efficiency KPIs to evaluate climb and descent performance across ten Canada's major airports. Based on an analysis of 158,660 departure flights and 155,840 arrival flights crossing Canadian airspace, this study characterizes patterns of vertical flight efficiency across major Canadian airports. Rather than attributing causality, the results highlight systematic differences in efficiency across airports and over time, including variations observed during the winter–spring transition period covered by the dataset. Differences between western airports (e.g., Vancouver area) and eastern airports (e.g., Toronto, Montréal, Québec) are also observed, reflecting distinct operational and environmental contexts. The findings therefore emphasize the role of traffic intensity, regional operating environments, and short-term temporal variability in shaping observed vertical efficiency outcomes. Vancouver shows greater inefficiency during the climb phase than Montréal and Toronto. At both eastern hubs, climb times increased by 105% from January to April 2025, coinciding with the seasonal transition from winter to spring. Descent phases are generally less efficient than climbs, especially at Vancouver and Toronto, where level-off durations frequently exceed five minutes. Montréal and Ottawa also show notable inefficiencies, with average durations exceeding three minutes. Calgary, benefiting from less congested airspace, shows better overall performance compared to the other major hubs, while Winnipeg demonstrates efficient descents but inefficient climbs. Targeted measures such as segregated arrival/departure corridors and time-based metering at Vancouver and Toronto are suggested to improve vertical efficiency. This research contributes to establishing a versatile tool for continuous ATM performance monitoring and collaborative optimization across international boundaries.

Keywords: air traffic management, key-performance indicators, data mining, level-off

1. Introduction

Aviation's global infrastructure is experiencing unprecedented strain as passenger demand outpaces system capacity enhancements, resulting in widespread operational disruptions that affect economic and environmental outcomes. This congestion becomes particularly evident during high-traffic periods, highlighting the urgent need for a comprehensive analysis of airspace utilization patterns, operational constraints, and network efficiency to develop effective strategic solutions. Progress toward optimization has been hampered by disparate information systems, with essential operational data, including flight trajectories, fleet management, and air traffic control directives distributed

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across various stakeholders without adequate integration mechanisms [1].

Performance degradation in air transport is mainly due to suboptimal vertical flight profiles within Terminal Maneuvering Areas (TMAs) and deviations of the route required by adverse weather conditions. Punctuality remains a critical concern among aviation stakeholders, as delays generate substantial tactical and strategic costs for airlines, airports, and passengers while producing avoidable environmental impacts through increased fuel consumption and emissions [2]. Addressing these challenges requires implementing a Performance-Based Approach (PBA) for air traffic management. This approach entails a methodical framework for evaluating operational performance to support decision-making. This approach aligns with the International Civil Aviation Organization's (ICAO) Global Air Navigation Plan (GANP), which establishes key performance areas indicators essential for monitoring system efficiency. These metrics provide valuable reference points for innovation initiatives that take advantage of advanced technologies such as big data analytics and machine learning algorithms.

In this context, the take-off and landing phases represent particularly complex operational segments, requiring attention from controllers and pilots, while generating environmental impacts due to operations at lower altitudes. With that, the Single European Sky ATM Research program (SESAR) created the Continuous Climb Operations (CCOs) and Continuous Descent Operations (CDOs) as intruments to offer promising solutions within the PBA framework. According to Eurocontrol [3], these techniques enable aircraft to follow optimized flight paths that simultaneously reduce fuel consumption, minimize emissions, reduce noise pollution, and lower operational costs while maintaining rigorous safety standards.

Building on previous efforts to evaluate more predictable continuous descent operations, such as those described in [4], [5], and [6], this study advances the KPI analysis with even more open-source data. More recent studies, such as [7, 8], leverage data-driven and trajectory-based approaches to analyze aircraft performance metrics across different flight phases, highlighting the growing role of open operational data in modern ATM performance assessment. We provide a quantitative assessment of vertical flight efficiency at Canada's ten busiest airports by analyzing aircraft trajectory parameters, including velocity, climb and descent rates, and altitude profiles relative to runway position. The research focuses specifically on two critical GANP KPIs: level-off during climb and level-off during descent. By calculating the duration and distance of level-flight segments, we identify deviations from continuous climb and descent profiles, using comprehensive trajectory data spanning six months (November 2024 to April 2025) obtained from the OpenSky Network (OSN). This open-source approach ensures research reproducibility and facilitates future comparative analyses across different national airspace systems.

2. Methodology

2.1 Dataset

Automatic Dependent Surveillance–Broadcast (ADS-B) serves as a foundation for dependable aircraft trajectory data transmission worldwide. It allows position tracking and data transmission through satellites in real time, which improves air travel safety. By supplying air traffic control with immediate information, ADS-B aids decision making processes in air traffic management. This information proves valuable for performance evaluation, continuous monitoring, and long term planning. Various global flight tracking service providers, including Flightradar24 (FR24) and OSN, manage large networks of ADS-B receivers to gather and distribute current flight data.

The dataset used in this research contains flight tracking data that encompasses Canadian airspace collected from the historical database of the OSN, a community based ground sensor network that collects air traffic data from signals continuously broadcast by aircraft. We collected the data over six months, from November 2024 to April 2025. For data collection, we defined a geographic bounding box encompassing Canada. The bounding box is specified by the coordinates (41.7, 83.1, -141.0, -52.6), where the first two values represent the southernmost and northernmost latitudes, and the latter two denote the westernmost and easternmost longitudes, respectively.

This research focuses on air traffic at the top ten busiest airports in Canada, selected based on the traffic data collected. Table 1 lists each airport's ICAO code, location coordinates, and flight count.

Table 1. Information of the top airports in Canada.

ICAO	City	# of Flights
CYVR	Vancouver	31,313
CYYZ	Toronto/Pearson	31,000
CYYC	Calgary	20,765
CYUL	Montréal	18,815
CYWG	Winnipeg	11,356
CYQT	Thunder Bay	10,974
CYEG	Edmonton	9,366
CYOW	Ottawa	8,114
CYTZ	Toronto/Billy Bishop	7,244
CYQB	Québec	7,005

Figure 1a illustrates all flight trajectories recorded on January 1st, 2025, while Figure 1b highlights the trajectories of flights that either departed from or arrived at one of the ten busiest airports. To identify climb and descent trajectories, flights were first selected based on the ICAO codes of their departure or arrival airports, and trajectory points were then extracted within the corresponding terminal area of each airport, following the same procedure for departures and arrivals. As can be seen, because the data was collected using a rectangular bounding box around Canada, some domestic flights within the United States, such as those in Montana and Wyoming, may appear in the dataset and require filtering.

Each black line in the dataset represents a flight trajectory with at least one coordinate point inside the Canadian bounding box. A color opacity scale was also applied, with darker lines representing flights on more frequently traveled routes. Using a rectangular bounding box for data collection creates certain constraints. Domestic flights within north and northeastern United States appear in the raw dataset when their paths cross the bounding boxes. Furthermore, international flights between countries outside Canada may exist in the dataset if their routes intersect the bounding boxes of the country. This inclusion ensures thorough coverage of all relevant flight activities within the specified regions but requires careful filtering to isolate flights relevant for analysis.

Figure 2 displays the flight trajectories on January 1st, 2025, associated with two major Canadian airport hubs: Vancouver International Airport (CYVR) and Toronto Pearson International Airport (CYYZ). The raw trajectory data was collected using the REST API provided by OSN, which returns an aircraft's flight path as a sequence of waypoints. Each waypoint includes a timestamp, geographic coordinates, barometric altitude, true track, and an on-ground status flag. However, OSN trajectory data alone does not include the ICAO codes for the departure or arrival airports associated with a flight. To address this, the trajectory data was joined with OSN's flights dataset, which contains additional metadata such as the unique ICAO 24-bit transponder address (in hexadecimal string format), the aircraft callsign, and the ICAO codes for both the origin and destination airports.

To uniquely identify each flight in our dataset, we concatenated the ICAO 24-bit address, the call-

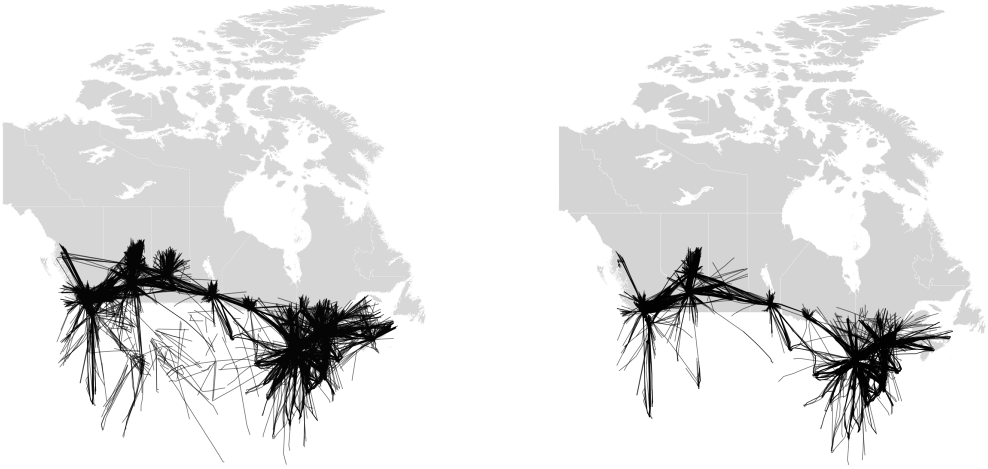

(a) All. **(b)** Top-10.

Figure 1. Flight trajectories crossing a rectangular bounding box covering Canada, from flights departing or arriving on January 1st, 2025.

sign, and the first timestamp (in UNIX time format) to generate a unique identifier, referred to as `flight_id`.

In many cases, OSN provides either the departure or arrival airport ICAO code, but not both, particularly when the trajectory is incomplete. This can hinder the calculation of KPIs for a given TMAs. To mitigate this issue, we split the dataset into two subsets: `DEP_Database`, containing flights with known departure ICAO codes, and `ARR_Database`, containing flights with known arrival ICAO codes. This separation enables us to compute KPIs for either the departure or arrival TMAs, even when the full trajectory is not available.

2.2 Pre-processing

The data preprocessing workflow involved a series of computational functions designed to enrich the dataset and support the calculation of KPIs. First, we added four new columns to the dataset to store the latitude and longitude of both the departure and arrival airports. Using these coordinates, we computed the distance, in nautical miles (NM), between each point in the flight trajectory and the departure and arrival airports.

This allowed us to determine whether an aircraft was operating within a TMA of 200 NM at the destination airport, for example. According to the GANP guidelines [9], KPIs related to climb and descent profiles should be computed using standardized terminal areas defined by 200 NM radius circles, ensuring that all terminals have the same spatial extent so that the time spent inside the terminal airspace is comparable and not biased by differences in terminal size, as documented in the GANP [10, 11].

The use of a fixed 200 NM terminal radius does not introduce bias for airports located near the US border, as the KPI is defined with respect to the arrival or departure airport, not to national airspace boundaries. The efficiency assessment is therefore airport-centric: for instance, if a flight lands at Vancouver, the KPI measures the aircraft behavior within the 200 NM terminal centered on that Canadian airport, even if part of this circular area geographically overlaps with US airspace (e.g.,

(a) Vancouver.

(b) Toronto.

Figure 2. Flight trajectories for Vancouver and Toronto on January 1st, 2025.

near Seattle). In this context, FIR or national airspace sectorization does not affect the KPI definition or its interpretation, since the metric focuses exclusively on the time or distance spent in climb or approach phases within standardized 200 NM circular terminals. This ensures consistency and comparability across all airports, independently of their proximity to international borders.

Additionally, we introduced a new column to classify the flight phase based on the aircraft's proximity to the departure and arrival airports. This classification allows us to determine, for each trajectory point, whether the aircraft is almost on the ground (`GND`), arriving at the destination (`ARR`), departing from the origin (`DEP`), or en route (`ENR`). The logic used for classification was as follows:

- `GND_ARR`: if the great-circle distance from the current lat/lon to the arrival airport ≤ 5 NM
- `ARR_40`: if the great-circle distance from the current lat/lon to the arrival airport ≤ 40 NM
- `ARR_100`: if the great-circle distance from the current lat/lon to the arrival airport ≤ 100 NM
- `GND_DEP`: if the great-circle distance from the current lat/lon to the departure airport ≤ 5 NM
- `DEP_40`: if the great-circle distance from the current lat/lon to the departure airport ≤ 40 NM
- `DEP_100`: if the great-circle distance from the current lat/lon to the departure airport ≤ 100 NM
- `ENR`: otherwise

This classification enables more granular analysis of aircraft behavior across different flight phases and supports the extraction of TMA-specific KPIs.

2.3 Data filtering and cleaning

The data filtering process involved selecting only the flights whose departure or arrival airport ICAO codes matched those of the top ten busiest airports.

Several data irregularities were identified in the OSN trajectory data. For instance, some trajectories included repeated waypoints over advancing timestamps, implying that an aircraft remained stationary in the air. Other anomalies involved implausible latitude and longitude values that deviated significantly from the expected flight path, as well as erroneous speed measurements. Flights exhibiting any of the anomalies described above were excluded from the dataset.

When calculating the level-off during climb KPI, we considered only flights that included at least one trajectory point within the `DEP_40` phase, i.e., within a 40 NM radius of the departure airport. Similarly, for the level-off during descent KPI, we required at least one trajectory point within the `ARR_40` phase. For climb analyses, we restricted the dataset to flights with a known departure ICAO code, using only entries from the `DEP_Database`. Conversely, descent analyses were based exclusively on the `ARR_Database`. Additionally, we excluded flight trajectories with fewer than five data points and removed any duplicated flights to ensure data integrity.

2.4 Performance analysis

GANP outlines 23 KPIs for evaluating airspace efficiency. This study examines 2 KPIs that utilize the flight track data collected. These KPIs were selected based on their ability to thoroughly assess airspace performance, as they collectively measure vertical efficiency of flight trajectories.

- **Vertical efficiency during climb (KPI 17):** This metric assesses vertical inefficiencies during climb by identifying level-offs segments, defined as portions where the climb rate is below 300 ft/min, within 200 NM of the departure airport. To distinguish operational inefficiencies from aircraft performance management near cruise altitude, an exclusion box is applied. This box spans from 90% to 100% of the maximum altitude reached within that radius, omitting level segments within this range. The Top of Climb (TOC) is defined as the highest altitude achieved within 200 NM, excluding those within the box.
  Figure 3 illustrates this definition, as well as which level segments will be considered and which will be excluded by the exclusion box.

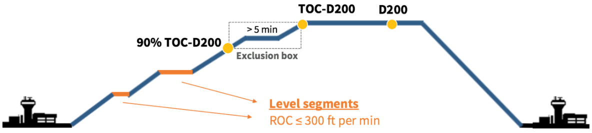


Figure 3. Definition of exclusion boxes and level-offs for KPI 17.

The key parameters used, based on GANP guidelines [10], include:
- TMA radius: 200 NM
- Vertical speed threshold: 300 ft/min
- Level band: 300 ft
- Analysis window: 20 sec
- 90% of cruising altitude
- Minimum altitude for analysis: 3000 ft AGL
- Max duration inside exclusion box: 5 min

The indicator is calculated in two forms: by distance (in NM) and by time (in minutes), as shown in Equation 1:

$$\frac{\sum_{i=1}^{N} \sum_{j=1}^{L} l_{ij}}{N} \tag{1}$$

Where:
- i: flight index

  - l: length or duration of level segment
  - L: number of level segments
  - N: total number of flights

- **Vertical efficiency during descent (KPI 19):** This metric mirrors the climb phase approach but focuses on level segments during descent within 200 NM of the arrival airport. Level segments are identified where descent rate falls below 300 ft/min, and the same 90% exclusion box is applied relative to the maximum descent phase altitude. The Top of Descent (TOD) is defined as the highest point within this 200 NM approach window, excluding those within the exclusion zone. Figure 4 illustrates this definition.

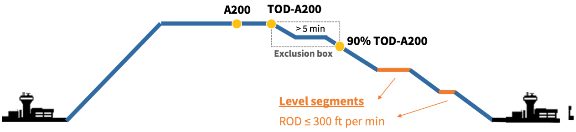


Figure 4. Definition of exclusion boxes and leveled segments for KPI 19.

The key parameters used, based on GANP guidelines [11], include:

  - TMA radius: 200 NM
  - Vertical speed threshold: 300 ft/min
  - Level band: 300 ft
  - Analysis window: 20 sec
  - Exclusion box threshold: 90%
  - Final descent floor: 1800 ft AGL
  - Max duration inside exclusion box: 5 min

The descent efficiency KPI is also computed in two forms: distance (in NM) and time (in minutes), using the same formula structure (Equation 1) as for climb efficiency.

3. Results

3.1 Data filtering and cleaning

We clarify that the exclusion of flights was performed solely to facilitate the KPI computation, as our objective was to work exclusively with fully observed real trajectories, without applying resampling techniques or removing partial segments of the trajectories. The proposed KPIs are designed to be entirely data-oriented, meaning that any manipulation of the original data, such as deleting waypoints or correcting inconsistencies (e.g., latitude and longitude changing while timestamps remain frozen), would no longer faithfully represent the trajectory as it was collected from the real flight.

The excluded flights mainly correspond to incomplete or inconsistent trajectories, including cases where the trajectory does not cross the 200 NM terminal boundary (e.g., trajectories containing only cruise segments) or presents temporal inconsistencies that would compromise the KPI calculation. In total, 24.0% of departure trajectories and 14.7% of arrival trajectories were excluded.

Despite these exclusions, the final dataset still comprises more than 170,000 analyzed flights, which is significantly larger than what is typically reported in the literature, where studies often rely on much shorter time windows (e.g., one week of operations). Therefore, the exclusions do not compromise the robustness or representativeness of the results, while ensuring methodological consistency and transparency in the KPI computation. Note that not all of complete flights are used in KPI calculation. For example, flights that have all the departure trajectory below the threshold of 3000 ft AGL are not considered for the analisys, since this is the minimum altitude used based on GANP guidelines. Table 2 provides detailed numbers.

Table 2. Data filtering and KPI calculation summary for Canadian flights.

Metric	Departures	Arrivals
Original flights (raw)	158,660	155,840
Flights at top-10 airports	81,937	73,993
Filtered flights	62,336	63,118
Percentage of complete flights	76.0%	85.3%
Total unique flights	177,710	
KPI flights (KPI 17)	49,443	
KPI flights (KPI 19)	53,492	

Flights are filtered through a three-level hierarchy to ensure data quality and KPI relevance. Filtered flights remove overflights, trajectories outside the 200 NM terminal area, or flights with major data issues. Complete flights are a subset with full trajectory information suitable for general analysis. KPI flights are the final subset meeting all criteria for KPI computation (e.g., trajectory above the 3,000 ft AGL), such as altitude thresholds, with "KPI flights (level-off climb)" specifically identifying level-off segments during departures.

3.2 KPI 17

Figure 5 illustrates the monthly evolution of the average distance and time flown in level segments during the climb phase, from November 2024 to April 2025.

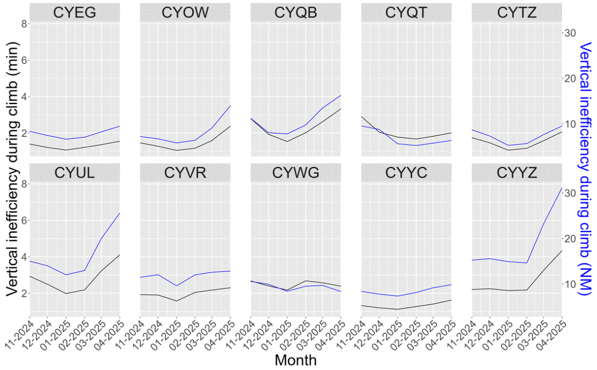


Figure 5. Mean KPI 17 for the top-10 busiest Canadian airports from November 2024 to April 2025.

While CYVR led the overall traffic ranking as the airport with the highest number of flights, it consistently exhibited lower average KPI values during the six-month period when compared to CYUL and CYYZ. In contrast, CYUL and CYYZ maintained higher and more consistent averages. Figure 6 ranks the airports, with Montréal, Toronto, Winnipeg, and Québec showing the least efficient climb performances.

A notable increase in average KPI values is observed in March and April 2025, particularly at CYUL and CYYZ. From January to April 2025, the KPI value increased by 104.8% at CYYZ and by 105% at

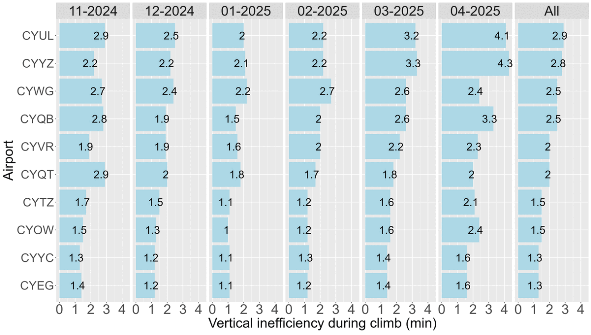


Figure 6. Ranking of KPI 17 from November 2024 to April 2025.

CYUL.

Figure 7 presents the horizontal profiles of departures from CYYZ in April 2025, the month with the lowest vertical efficiency. Blue lines indicate segments where the aircraft followed a CCO, while orange lines highlight level-off segments (i.e., rate of climb dropped below 300 ft/min).

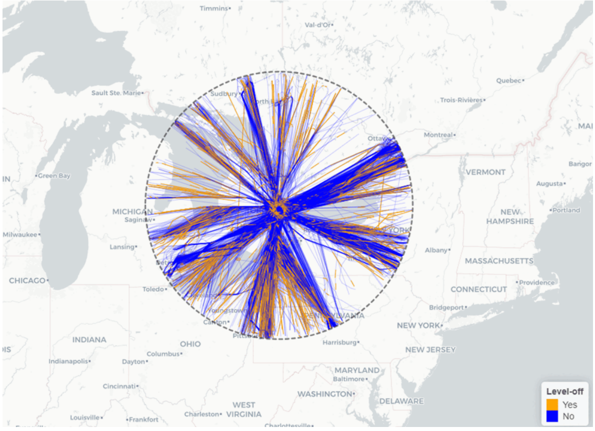


Figure 7. Horizontal profile of KPI 17 at CYYZ in April 2025.

Based on the visual evidence provided by the figure, level-off occurrences appear to be distributed across different parts of the terminal area rather than being confined to a single region. Level-offs are visible both close to the runway shortly after takeoff and farther from the airport, near the TMA boundary, indicating that these events may occur at different locations within the terminal airspace.

To further investigate these changes, the performance analysis allows visualization of vertical flight profiles along with KPI values. Figure 8 illustrates the vertical profiles of trajectories departing from CYUL. From left to right, each curve represents an individual aircraft's climbing phase in terms of distance flown from runway departure up to the point where it exits the TMA at 200 NM, or reaches its destination airport if it is located closer. Warmer colors represent more inefficient trajectories.

It is possible to observe several level-offs occurring in the altitude range from 5,000 ft to 10,000 ft. To better isolate the data and enable a more localized analysis, Figure 9a presents the vertical profiles of flights departing from CYYZ on a single day in January. For comparison, Figure 9b displays the corresponding profiles for the same airport and calendar day in April.

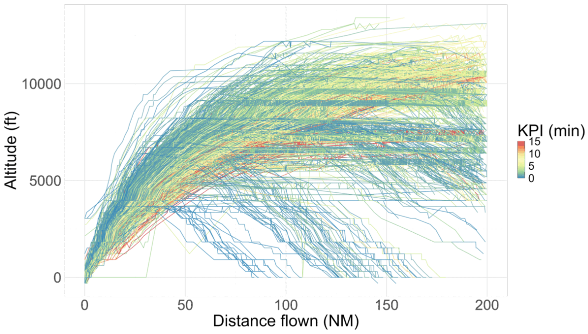
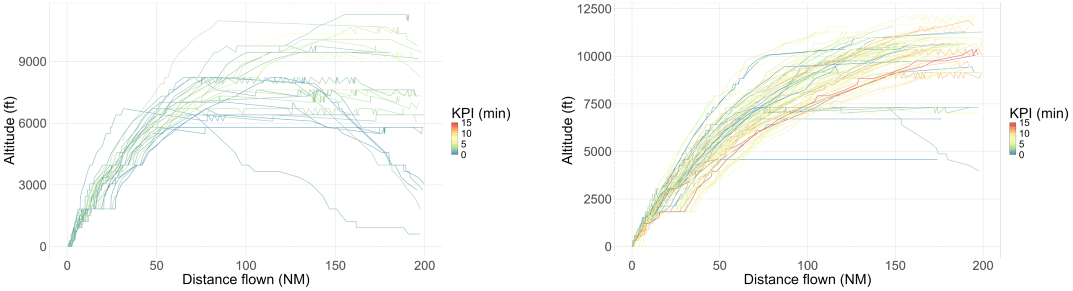


Figure 8. Vertical profile of trajectories during climb at CYUL in April 2025.



(a) January 06th, 2025.

(b) April 06th, 2025.

Figure 9. Vertical profiles of trajectories departing from CYYZ.

As expected, the number of level-off events increased in April compared to January, resulting in a higher KPI value. This can be attributed to the seasonal transition from winter to spring, which introduces various operational and meteorological challenges. A significant contributing factor is the 30.1% increase in total flights at CYYZ during this period, likely driven by a resurgence in tourism and business travel after the winter months.

Figure 10 shows the trend graph of mean altitude of level-off revealing the average altitude at which aircraft maintain level flight segments during the climb phase. The presence of stable altitudes associated with level-offs may be attributed to operational inefficiencies, as suggested, for example, in [12].

Over the six-month period, the mean level-off altitude remained relatively stable, with slight fluctuations from month to month. Flights departing from CYYC, CYYZ, and CYEG tend to level-off at higher altitudes, which is preferable compared to leveling off below 6,000 ft, as observed at CYWG. This suggests a consistent operational behavior, though periods with lower average altitudes may indicate more constrained climbs due to weather conditions or air traffic control interventions.

Supporting this analysis, we generates boxplots to assess the dispersion of the KPI across the analyzed airports. While the mean KPI provides a general trend of vertical efficiency over time, the boxplots offer a deeper look into the variability of performance, highlighting airports with higher or lower operational consistency. In all boxplots of this section, the top 2% KPI values were removed to improve visualization.

Figure 11a displays a scatter plot of KPI dispersion over the six-month period. As anticipated, CYYZ,

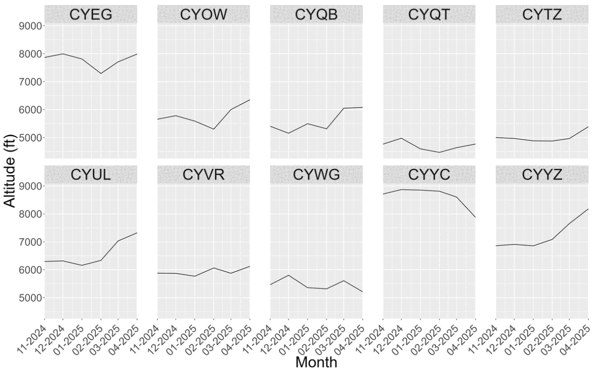
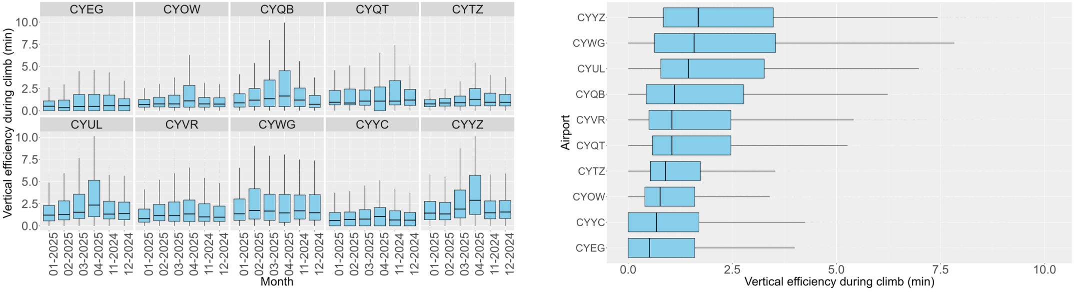


Figure 10. Mean altitude of level-off during climb for the top-10 busiest airports from November 2024 to April 2025.

CYWG, and CYUL exhibit the greatest variability. Meanwhile, Figure 11b presents an aggregated boxplot, revealing that the third quartile remains below 4 minutes for all airports, demonstrates good compliance with ICAO's vertical flight efficiency standards [13]. Interestingly, despite its lower traffic volume relative to major hubs, CYWG shows considerable KPI dispersion, indicating variability in operational performance that warrants further investigation.



(a) Scatter plot.

(b) Aggregated plot.

Figure 11. Boxplots of KPI 17 for the top-10 busiest airports.

It is important to avoid level flights during the climb phase, as they tend to result in higher fuel consumption and potentially increased noise levels, as highlighted.

3.3 KPI 19

Figure 12 presents the monthly evolution of the average distance and time flown in level segments during the descent phase, covering the period from November 2024 to April 2025.

Although CYWG exhibited high KPI values for level-offs during climb, it demonstrated one of the most efficient performances during the descent phase. This could be attributed to lower arrival congestion, enabling more CDOs. Local factors at Winnipeg may also play a role, such as more constrained departure corridors compared to arrival paths, as well as weather conditions that may disproportionately affect climb profiles (e.g., low-level wind shear patterns).

With CYWG as an exception, the general trend reveals that most airports face greater operational challenges in managing the descent phase than the climb phase. This is reflected in higher KPI values, often exceeding 7.5 minutes of level-off at major hubs such as CYYZ and CYVR. The analysis

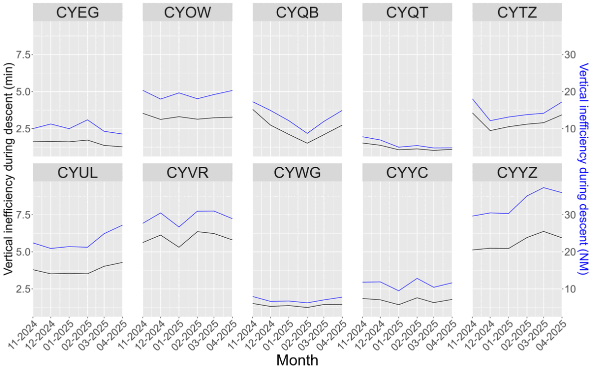


Figure 12. Mean KPI 19 for the top-10 busiest Canadian airports from November 2024 to April 2025.

includes 12,406 arrival flights and 9,800 departure flights at CYYZ, as well as 9,503 arrival flights at CYYZ and 8,724 departure flights at CYVR. These inefficiencies are therefore expected given the high traffic volumes and airspace complexity at these airports, particularly during peak arrival periods.

Notably, CYOW, which performs efficiently during climb, shows signs of inefficiency during descent. This may be influenced by its central location between two major hubs, Toronto and Montréal, where overlapping traffic flows increase arrival complexity.

Figure 13 presents the ranking of average KPI values during descent, with Vancouver and Toronto leading in inefficiency, each exceeding 5 minutes. Montréal and Ottawa also show notable inefficiencies, with average values surpassing 3 minutes.

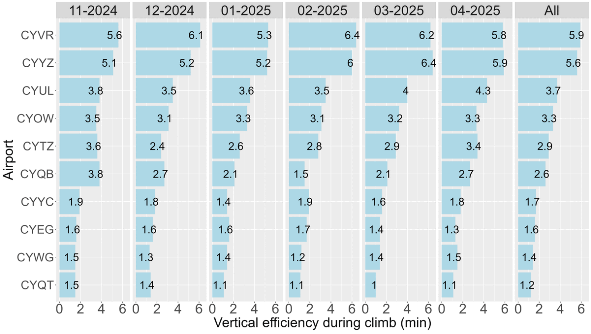


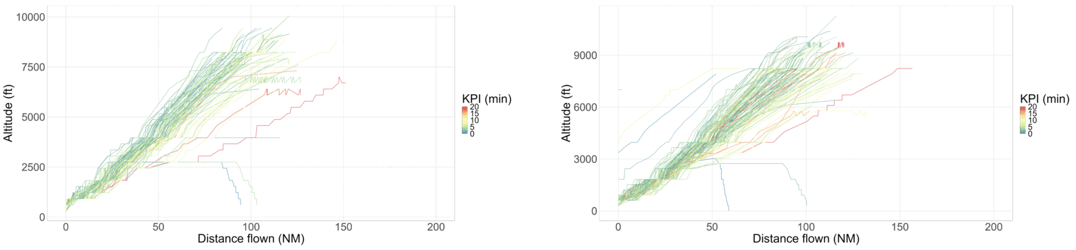
Figure 13. Ranking of KPI 19 for the top-10 busiest Canadian airports from November 2024 to April 2025.

It is interesting to observe that Calgary consistently exhibits lower KPI values for both climb and descent phases, despite being the third-busiest airport in the dataset. This performance can be partly attributed to the relatively uncongested airspace surrounding it, in contrast to CYYZ, which shares complex airspace with Montréal, or Vancouver, which operates near the busy Seattle terminal area in the United States. The lower density of surrounding airports likely reduces airspace complexity and potential conflicts. Additionally, Calgary experiences less international long-haul traffic compared to Toronto and Vancouver, further contributing to more streamlined operations. Operational factors, such as optimized procedures and CDOs may also enhance performance.

The fact that the KPI for descent is generally higher than for climb underscores the greater operational complexity associated with managing CDOs, both for pilots and air traffic controllers. Descent phases are often more sensitive to arrival sequencing, merging traffic flows, and variations in approach paths.

Seasonal effects are also reflected in this indicator. A notable increase in average KPI values is observed in March and April 2025, particularly at Vancouver, Québec City, and Toronto (both Pearson and Billy Bishop airports). From January to March 2025, the KPI increased by 16.98% for CYVR and by 23.07% for CYYZ, likely influenced by the transition from winter to spring.

Figure 14 illustrates the vertical profiles of trajectories arriving at CYYZ. These plots highlight more noncontinuous descent profile in March compared to January, with more level segments interrupting the ideal continuous descent path. From right to left, each curve represents an individual aircraft's descent phase in terms of distance flown, starting at its first entry into the 200 NM TMA and ending at runway landing (0 ft). Warmer colors indicate more inefficient trajectories, and an increased presence of level-off segments is visible in March..



(a) January 1st, 2025.

(b) March 1st, 2025.

Figure 14. Vertical profiles of trajectories arriving at CYYZ.

The plots show the arrival profiles of aircraft landing at CYYZ on two representative days, one in January and one in March 2025. For comparison, Figure 15 presents all descent profiles at CYVR on March, 2025.

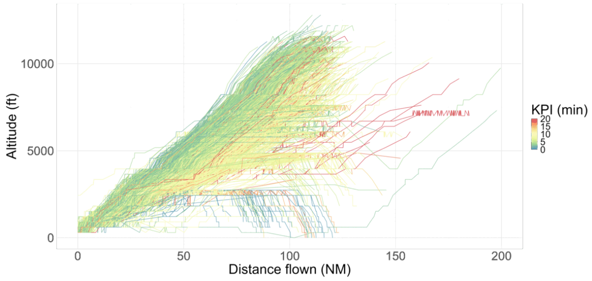


Figure 15. Vertical profiles of arriving aircraft at CYVR on March, 2025.

It is evident that most level-offs at CYVR occur below 7,000 ft. To confirm this observation, Figure 16 illustrates the mean level-off altitudes during descent across the top-10 busiest Canadian airports from November 2024 to April 2025.

This indicator shows little variation throughout the six-month period. However, airports such as CYEG and CYYC display higher average level-off altitudes, correlating with their overall better KPI performance. CYVR despite already having a high level of descent inefficiency, with an average level-off duration of around 5.9 minutes, shows that most of level-offs occur at lower altitudes (below 7,000 ft), exacerbating fuel consumption and emissions. This presents a clear opportunity for

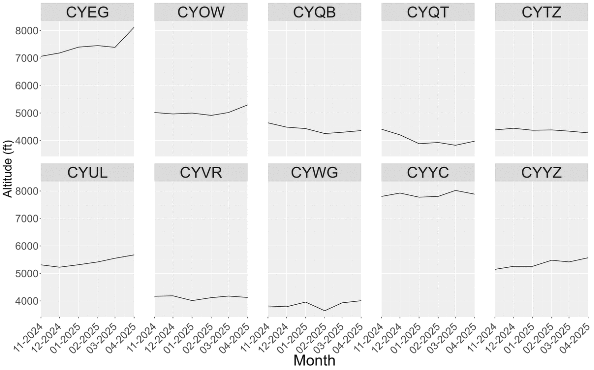
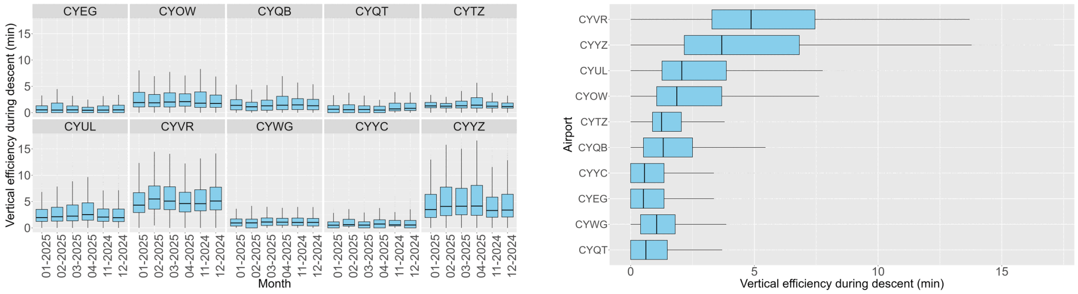


Figure 16. Mean level-off altitude during descent for the top-10 busiest airports from November 2024 to April 2025.

improvement.

These findings support the use of PBA combined with data mining techniques to uncover operational inefficiencies and monitor the conformity of the ATM system. The results reinforce the need for improvement in terminal area operations, particularly at major international hubs such as CYUL, CYYZ, and CYVR.

Figure 17 provides further evidence through boxplots illustrating the dispersion of the KPI across the period. Figure 17a presents a monthly scatter of KPI values, while Figure 17b shows the aggregated performance. Airports like Vancouver and Toronto shows greater variability, underscoring the complexity of their terminal airspace and the prevalence of level-offs.



(a) Monthly scatter plot.

(b) Aggregated boxplot.

Figure 17. Boxplots of KPI 19 for the top-10 busiest airports.

For both CYVR and CYYZ, the third quartile exceeds 5 minutes, with Vancouver recording the worst overall KPI performance. These values suggest persistent inefficiencies rather than sporadic operational disruptions. Addressing these issues may require airspace redesign to create more segregated arrival and departure corridors and implementing time-based metering to better sequence arrivals that could reduce the reliance on tactical level-offs and improve overall vertical efficiency.

The scope of this study is intentionally limited to assessing performance trends and identifying relatively more or less efficient airports and regions, rather than attributing causality to specific operational factors. While published SID and STAR procedures may indeed influence the occurrence of level-offs, since more restrictive or indirect procedures can inherently limit the feasibility of CCOs/CDOs, this effect is considered part of the structural operating environment of each airport. As such, the KPI captures the effective outcome of climb and descent operations as they are executed in practice, independently of whether constraints originate from procedural design, ATC actions, or other factors. A procedure-level analysis is therefore outside the scope of this work and left for future research.

4. Conclusions

This study established a robust analytical framework that correlates ADS-B surveillance data with ICAO KPIs related to vertical flight efficiency, as prescribed by the GANP. Using Canada as applied case studies, the analisys revealed distinct patterns of operational efficiency that correlate with airport size, geographic location, and seasonal factors. CYVR, despite handling the highest traffic volume, consistently demonstrated lower average climb KPI compared to CYUL and CYYZ. Notably, a significant increase in inefficiency was observed during the transition from winter to spring, with KPI values increasing by approximately 105% at both CYUL and CYYZ from January to April 2025.

At CYVR, the majority of inefficient level-offs occurred below 7,000 feet, precisely where fuel consumption and emissions impact is greatest. This contrasts with CYEG and CYYC, which maintained higher average level-off altitudes correlating with better overall KPI performance. CYWG exhibited poor performance during climbs but exemplary efficiency during descents, highlighting the complexity of local operational contexts. In CYVR and CYYZ, where mean level-off durations exceed 5 minutes, improvements could be achieved through airspace redesign that creates more segregated arrival and departure corridors, complemented by time-based metering to reduce tactical level-offs.

Future research should extend this approach to quantify the environmental and economic impacts of vertical inefficiencies. Unlike traditional air traffic analyses, our framework combines PBA with advanced data mining techniques to deliver actionable intelligence on system conformity and efficiency. The framework's versatility allows for adaptation to any airspace system that generates standardized trajectory data, creating opportunities for international benchmarking and collaborative optimization across international boundaries.

Author contributions

- Guilherme Trindade Tolentino Bernardo: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Software, Supervision, Validation, Visualization, Writing (Original Draft), Writing (Review and Editing)
- Marcelo Xavier Guterres: Writing (Review and Editing)
- Alexandre de Barros: Investigation, Writing (Review and Editing)

Open data statement

All datasets used in this research are openly available at the following Google Drive link: https://tinyurl.com/4vmufwcj. The file raw_df.Rda contains all raw flight records collected for this study, representing the unprocessed dataset obtained from the OpenSky Network. The file dep_filtered.Rda includes the processed departure flight data, which serves as the input for KPI calculations performed by the script KPI17.R. Similarly, the file arr_filtered.Rda contains the processed arrival flight data, which can be used in conjunction with the script KPI19.R to reproduce the results related to arrival performance. All datasets and corresponding codes necessary to replicate the analyses are provided in the shared repository.

Reproducibility statement

All the materials required to reproduce this research are publicly available on GitHub at https://github.com/guilhermebernardo/JOAS_2025.The files also can be found at https://tinyurl.com/4vmufwcj. This repository contains: (1) the source code used for data collection from the OpenSky Network (main_collect.R), (2) the scripts used for processing and calculating the KPIs—specifically process_data.R for KPI 17 and KPI 19, and (3) the scripts responsible for generating the figures and profiles presented in this paper (KPI19_print_charts.R, KPI19_print_profiles.R, KPI17_print_charts.R, and KPI17_print_profiles.R). The datasets kpi17.Rda and kpi19.Rda contain the computed KPI values for all flights analyzed in this research. To ensure full reproducibility, users should maintain the directory structure as indicated in the repository and save both the data and scripts accordingly. All codes are fully commented to facilitate understanding and replication of the methodology.

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