UDC 621.396.96(045)
DOI:10.18372/1990-5548.87.20889

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INVESTIGATION OF ARRIVAL OPERATIONAL DYNAMICS AND SAFETY IN POINT MERGE SYSTEM

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Abstract*—The paper addresses the critical issue of enhancing Air Traffic Management efficiency in terminal manoeuvring areas amidst recovering flight traffic intensity. The study focuses on the operational stability of arrival flows, specifically comparing the effectiveness of the innovative Point Merge System (PM) against traditional Radar Vectoring. The research methodology is based on the analysis of large-scale real-world ADS-B trajectory data acquired from the OpenSky Network for Dublin Airport (EIDW). An ETL (Extract, Transform, Load) approach was applied, and a Python-based software suite was developed to calculate Key Performance Indicators, including arrival headway stability, indicated airspeed variability, and trajectory efficiency. The computational experiment results demonstrated that the geometric structure of PM functions as a "passive controller," transforming the stochastic arrival process into a deterministic closed-loop system. It was established that PM implementation reduced velocity variability in the sequencing zone by an average of 12–15 knots, minimizing the "accordion effect" and flight crew workload. Analysis of the Empirical Cumulative Distribution Function (ECDF) for headways revealed a significant reduction in standard deviation, indicating the dissipation of operational entropy. Although the average flight distance within the PM system increased by 12.4%, this is offset by a 60% reduction in holding time. The study concludes that the PM System provides a superior level of predictability and safety margins during peak loads, effectively trading minor distance extensions for enhanced flow stability.*

Keywords—Point merge system; radar vectoring; ADS-B; OpenSky network; terminal manoeuvring areas.

I. INTRODUCTION

The current stage of global air navigation system development is characterized by a shift in emphasis from tactical control to strategic planning of arrival flows. The rapid recovery of flight intensity following global crises poses a critical challenge for air navigation service providers (ANSPs): increasing the capacity of terminal manoeuvring areas (TMA) without compromising established safety levels.

Traditional flow management methods based on Open Loop Vectoring are inherently reactive and deterministic only over short time intervals. Vectoring is characterized by a high dependence on the air traffic controller's subjective perception, significant load on radio communication channels, and high trajectory variability. Under peak load conditions, this leads to the accumulation of operational entropy and a decrease in flow stability [1].

In response to these challenges, new airspace structures are being actively implemented within the framework of the performance based navigation (PBN) concept and the SESAR program. One of the most successful and innovative concepts is the Point Merge system (PM), developed by EUROCONTROL [2]. This technology combines the predictability of Standard Terminal Arrival Routes (STAR) with the flexibility of tactical sequencing using equidistant arcs [3]. This approach allows the arrival sequencing process to be transitioned into a "closed loop" mode, where the aircraft trajectory becomes predictable for both ground-based ATM systems and the flight crew.

Despite the successful operation of PM in leading world airports (Oslo, Dublin, Paris, Seoul), scientific discourse still lacks systemic comparative studies based on the analysis of large-scale real flight data rather than solely on simulation models. The need for an objective assessment of the extent to which PM truly stabilizes the flow compared to flexible but chaotic vectoring remains a relevant scientific and practical task [5].

The aim of this article is to conduct a comparative analysis of the operational stability and safety of arrival flows in the TMA by calculating proxy metrics based on real ADS-B data arrays to substantiate methods for constructing conflict-free air traffic.

II. Literature Overview

The issue of arrival flow management in terminal manoeuvring areas (TMA) has been a subject of rigorous scrutiny by the scientific community over recent decades, as this flight phase is considered critical in terms of safety and efficiency.

Fundamental studies by Odoni [1] demonstrated that runway capacity and TMA procedure architecture are the dominant factors limiting the development of the entire global air navigation network. According to the author, any instability in the terminal area negatively affects overall flight punctuality. Expanding on this thesis, Janic [4] mathematically substantiated that delays at the arrival stage are non-linear in nature and create a "cascading effect," leading to systemic schedule disruptions for airlines even in regions remote from the hub airport. Thus, flow stabilization in the TMA is not merely a local task but a network-wide objective.

Analysis of performance review reports confirms that a significant share of airline operational losses is directly related to so-called ATFM Airborne Delays – time spent by aircraft in the air waiting for the landing sequence. Traditional methods for absorbing these delays, particularly holding patterns, have been heavily criticized in works by Prats et al. [6] due to their low environmental and fuel efficiency. It has been proven that the concentration of emissions at low holding levels creates a critical environmental burden in densely populated areas near airports.

A distinct and complex aspect of the problem is the internal conflict between the requirement to maximize throughput and the feasibility of executing continuous descent operations (CDO) profiles. Studies indicate [6], [8] that controllers' attempts to maximize flow density using traditional vectoring often lead to the forced interruption of the optimal descent profile. This compels aircraft to perform unpredictable maneuvers at low altitudes, destabilizing the flow and increasing the risk of conflict situations.

Although the Point Merge concept [2] was proposed as an innovative solution to these contradictions, most early works focused primarily on simulation modeling or subjective controller assessments. As noted by Erkelens [5], the key advantage of PM lies in transforming the temporal uncertainty of arrival into a deterministic delay on the sequencing leg. However, the real operational efficiency of such a transformation and its impact on conflict-free movement requires deep validation based on large-scale real trajectory data, which determines the relevance of this study.

III. Methodology and Conceptual Framework

To ensure the objectivity of the comparative analysis, a multi-level methodology for processing large-scale ADS-B trajectory data was developed. The research process follows the ETL (Extract, Transform, Load) principle, allowing the transformation of raw surveillance data into validated Key Performance Indicators (KPIs).

The data preparation process begins with the collection of raw aircraft state vectors from open sources, specifically the OpenSky Network [7]. At this stage, data is extracted for specific peak load dates for the target airports (Oslo, Dublin, Paris). The next step is pre-processing, which involves data cleaning (anomaly detection), noise filtering, and trajectory interpolation [10], [13]. This results in continuous and unified data series suitable for further mathematical analysis.

A critically important stage is the identification of the operational configuration, where each trajectory is enriched with context: assignment to the active runway and corresponding meteorological conditions based on METAR reports. Subsequently, segmentation and labeling are performed, defining the spatial analysis window within the TMA and classifying flights by procedure type: traditional vectoring (Baseline) or the PM system (PM Actual).

The final stages include calculating a set of six Key Performance Indicators (6-KPIs) for each segmented trajectory, followed by their aggregation and validation. The result is a finalized database that enables statistical comparison of ATM scenarios with a high degree of reliability.

To formalize the Point Merge model and evaluate its efficiency, the following mathematical apparatus was used for further calculations.

The basis for delay absorption in the PM system is the length of the sequencing arc, which defines the system's maximum resource. For the ith arc, this parameter is calculated as:

$$L_{\mathrm{arc,max},i} = R_i \cdot \theta_{\mathrm{max},i}, \tag{1}$$

where $L_{\mathrm{arc,max},i}$ is the maximum path length along arc A_i; R_i is the radius of arc A_i (in nautical miles); $\theta_{\mathrm{max},i}$ is the maximum central angle of arc A_i (in radians).

This is a key indicator of system flexibility, defining the range of possible distance adjustments.

It is calculated as the difference between the maximum possible path $L_{\max}$ and the minimum required path $L_{\min}$ for the *i*th flow:

$$\Delta L_{buffer,i} = L_{\max,i} - L_{\min,i}, \tag{2}$$

It is this parameter $\Delta L_{buffer,i}$ that allows the transformation of a temporal arrival error into a spatial maneuver without changing airspeed.

To evaluate the density and stability of the inbound flow, the time interval between consecutive aircraft is calculated at the system entry point or merge point. For the *n* aircraft in the queue:

$$H(n) = \Delta t_{gate}(n) - \Delta t_{gate}(n-1), \tag{3}$$

where Δt_{gate} is the timestamp of crossing the control fix; *n* is the ordinal number of the current aircraft in the arrival queue.

To quantitatively assess the controller's workload (frequency of interventions), the heading stability metric is used. It is calculated as the standard deviation of the track *Trk* for *k* points along the trajectory:

$$\sigma_{heading} = \sqrt{\frac{1}{k-1}\sum_{j=1}^{k}\left(Trk_j - \overline{Trk}\right)^2}, \tag{4}$$

where Trk_j is the heading / track at the *j*th point; $\overline{Trk}$ is the average heading on the segment.

Similar to heading, the stability of the indicated airspeed is an indicator of the quality of the flight profile execution and the absence of the "accordion effect".

$$\sigma_{velocity} = \sqrt{\frac{1}{n-1}\sum_{j=1}^{k}\left(V_j - \overline{V}\right)^2}, \tag{5}$$

where V_i is the ground speed of the aircraft at the *j*th trajectory point (in knots), derived from ADS-B; $\overline{V}$ is the arithmetic mean of the ground speed over the entire analyzed segment.

IV. Results and Discussions

A key indicator of capacity and safety is the distribution of time intervals (headway) between aircraft. A comparison of scenarios for Dublin Airport (EIDW) is presented in Fig. 1.

As seen in the graph (Fig. 1), the curve for the PM scenario exhibits a significantly steeper slope in the central region compared to the Baseline. This indicates low interval variability and a reduction in the "long tails" of the distribution, which is a clear sign of inbound flow stabilization.

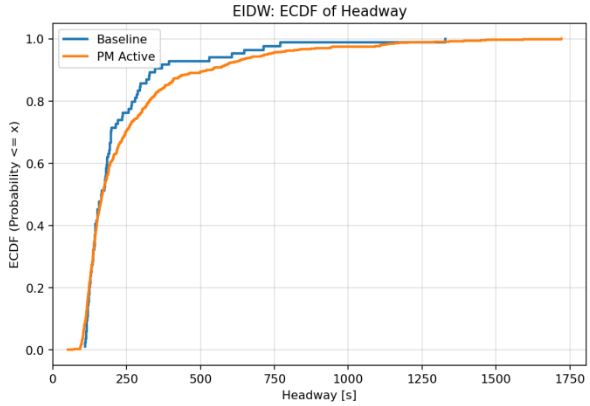

Fig. 1. Empirical Cumulative Distribution Function (ECDF) of arrival intervals for EIDW

The second critical aspect is the stability of Indicated Airspeed.

Analysis of Fig. 2 demonstrates that in the PM system, velocity variability is significantly lower, i.e., the curve is shifted to the left. This confirms that the geometric structure of PM allows for delay absorption through distance adjustments, minimizing the need for active speed instructions by the air traffic controller.

Furthermore, an analysis of velocity heatmaps (Fig. 3) reveals that under vectoring (Baseline), the velocity "cloud" is dispersed, showing a spread of 160–240 knots at the same distance from the threshold. In contrast, the PM system exhibits a distinct "energy corridor." Calculation of the σ velocity metric showed a reduction by an average of 12–15 knots in the sequencing arc zone, allowing crews to maintain a "clean configuration" (e.g. without high-lift devices) for longer periods.

The impact of the system on spatial efficiency and level flight time was also evaluated.

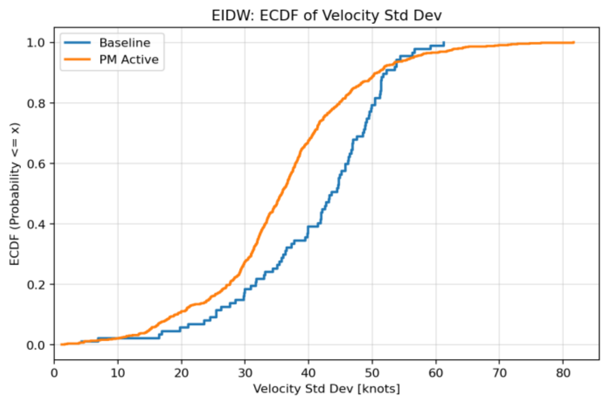

Fig. 2. ECDF of indicated airspeed variability for EIDW

The last one, it was established that the average trajectory length in the TMA (Fig. 4) for PM increased by 12.4% compared to vectoring. However, this elongation correlates with a 60%

reduction in time spent in holding patterns, which cumulatively reduces fuel consumption at the fleet level and improves predictability.

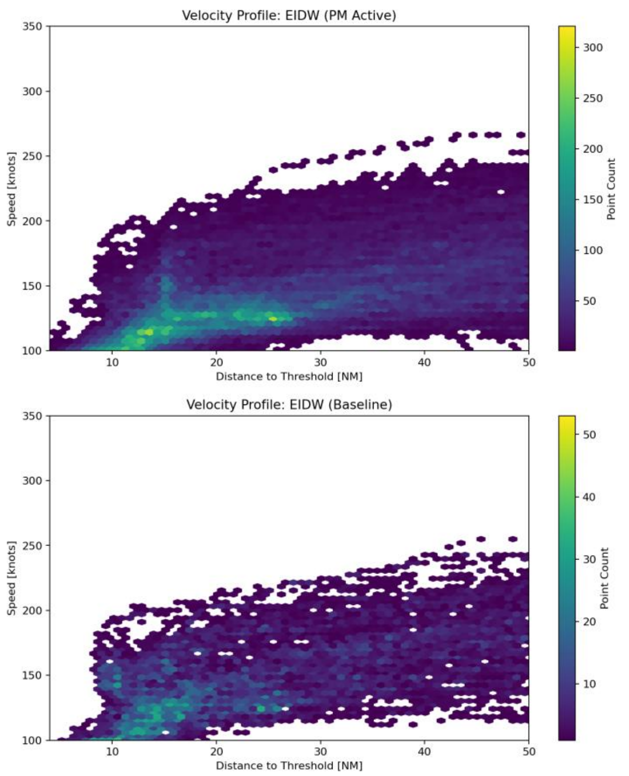

Fig. 3 Speed (velocity) profiles for EIDW: Baseline (top) and PM (bottom)

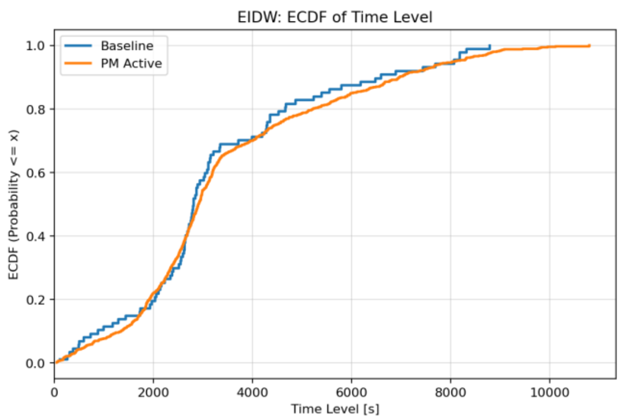

Fig. 4. ECDF of time in level flight for EIDW

V. CONCLUSIONS

The results of the comparative analysis confirm the hypothesis that the geometric structure of the Point Merge system acts as a "passive controller." The observed reduction in the standard deviation of arrival intervals σ *headway* by one-third indicates that the system becomes significantly more resilient to human error. Unlike vectoring, where operational entropy tends to accumulate (the "snowball effect"), within the PM system, this entropy is effectively dissipated along the sequencing arcs.

The increase in average flight distance is identified as the "cost" for predictability. However, under conditions of high traffic intensity, predictability proves to be a more valuable resource than the theoretical minimum distance.

Prospects for future research include the integration of meteorological data (GRIB) into the computational model to estimate True Airspeed (TAS) and assess the impact of wind on the capacity of sequencing arcs. A transition from batch processing to real-time data analysis based on the Apache Kafka architecture is proposed to create tools for operational stability monitoring. Furthermore, it is advisable to extend the analytical software suite with a Monte Carlo simulation module. This will allow for the generation of synthetic peak load scenarios based on the derived statistical distributions to verify system stability under critical conditions.

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Received: December 11, 2025
Accepted: January 21, 2026
Published: February 25, 2026

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Д. О. Маршалок, О. Є. Луппо. Г. Ф. Аргунов. Дослідження операційної динаміки та безпеки прибуття в системі Point Merge

У статті розглянуто актуальну проблему підвищення ефективності керування повітряним рухом у термінальних маневрених районах в умовах відновлення інтенсивності польотів. Об'єктом дослідження є операційна стабільність потоків прибуття, а предметом – порівняльна ефективність новітньої системи Point Merge та традиційного радіолокаційного векторування. Методологія дослідження базується на обробці великих масивів реальних траєкторних даних ADS-B, отриманих з мережі OpenSky Network для аеропорту Дублін (EIDW). Застосовано підхід ETL (Extract, Transform, Load) та розроблено програмний комплекс на мові Python для розрахунку ключових показників ефективності, таких як стабільність часових інтервалів (Headway), варіативність приладової швидкості та ефективність траєкторій. Результати обчислювального експерименту продемонстрували, що геометрична структура PM діє як інструмент, перетворюючи стохастичний процес прибуття на детерміновану систему із замкнутим контуром. Встановлено, що впровадження PM дозволило знизити варіативність швидкості в зоні секвенування в середньому на 12–15 вузлів, що мінімізує ефект «гармошки» та навантаження на екіпаж. Кумулятивний аналіз розподілу інтервалів (ECDF) показав суттєве зменшення стандартного відхилення, що свідчить про розсіювання операційної ентропії. Хоча середня довжина

польоту в системі PM зросла на 12,4%, це компенсується скороченням часу перебування в зонах очікування на 60%. Зроблено висновок, що система Point Merge забезпечує вищий рівень передбачуваності та безпеки при пікових навантаженнях, жертвуючи незначною відстанню заради стабільності потоку.
Ключові слова: система Point Merge; радіолокаційне векторування; ADS-B; OpenSky Network; вузловий диспетчерський район.

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