

Estimation and Analysis of RNP Requirements for Heterogeneous UAM Configurations: Insights from OPPAV Demonstration

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Abstract

The successful commercialization of Urban Air Mobility (UAM) necessitates a paradigm shift from traditional air traffic management to operations within complex urban canyons. In this constrained environment, the implementation of Performance-Based Navigation (PBN), specifically the Required Navigation Performance (RNP) concept, is not merely advantageous but absolutely essential to ensure operational safety and airspace capacity through precise procedural separation. Unlike conventional aviation, the UAM ecosystem will be populated by a heterogeneous fleet of electric Vertical Take-Off and Landing (eVTOL) aircraft ranging from multicopters to lift-plus-cruise and vectored-thrust configurations each possessing distinct aerodynamic, control and performance characteristics. Consequently, a uniform navigation standard may be insufficient; instead, RNP requirements must be derived from a rigorous analysis of specific vehicle performance capabilities across different flight phases to accommodate diverse performance characteristics.

This study presents a comprehensive estimation of RNP requirements for UAM operations, leveraging empirical flight data from OPPAV demonstration flights conducted in both non-urban and urban operational environments in South Korea. We analyzed the flight trajectories of the KARI OPPAV (Optionally Piloted Personal Air Vehicle), a representative lift-plus-cruise aircraft equipped with fixed wings for cruising and independent rotors for lift. The research methodology involved decomposing the Total System Error (TSE) into Navigation System Error (NSE) and Flight Technical Error (FTE) across distinct flight segments (straight vs. turning) to quantify the safety margins required for urban corridors.

Our analysis reveals that in a high-precision Real-Time Kinematic (RTK) GNSS environment, NSE is negligible, making FTE the dominant factor in determining RNP levels. The OPPAV demonstrated the capability to maintain an RNP 0.02 specification, significantly surpassing the current aviation standard of RNP 0.3. However, the study identified critical performance variations depending on flight segment geometry and operational environment. The analysis revealed distinct tracking characteristics between straight and turning segments, indicating that navigation performance can vary depending on flight segment geometry and operational conditions. These findings suggest that UAM airspace design must adopt the concept of 'Adaptive RNP' criteria that account for segment-dependent tracking characteristics and varying operational environments. This paper provides foundational quantitative data for establishing airspace design guidelines for the safe integration of diverse UAM vehicles into the national airspace system.

Keywords: Urban Air Mobility (UAM), Required Navigation Performance (RNP), Flight Technical Error (FTE), Optionally Piloted Personal Air Vehicle (OPPAV), Performance-Based Navigation (PBN)

1. Introduction

Flight-path tracking performance is a critical factor that directly affects operational safety and mission efficiency in emerging urban air mobility (UAM) operations. Performance-Based Navigation (PBN) provides a framework for designing and operating airspace and flight procedures based on Required Navigation Performance (RNP) [1]. In particular, RNP operations require quantitative metrics to evaluate navigation and tracking performance. In constrained urban environments, accurate flight-

path tracking directly affects procedural separation, operational safety, and corridor capacity, emphasizing the need to establish appropriate RNP requirement levels [1-3].

Although previous studies have investigated navigation performance for conventional aviation and UAM operations, limited research has addressed segment-wise RNP requirement estimation using empirical flight demonstration data in diverse operational environments [4-7]. Flight Technical Error (FTE) is a key performance indicator representing the deviation between an actual flight trajectory and a predefined reference path. In dense urban environments, UAM flight paths may contain diverse geometries, including straight and turning segments. Accordingly, tracking characteristics and error distributions can vary depending on the flight segment type. Therefore, defining navigation performance requirements based on segment-wise error analysis is essential for supporting PBN implementation in urban UAM demonstration operations. Nevertheless, limited work has investigated how flight-segment geometry influences TSE characteristics and the resulting RNP requirements using operational flight data, despite several studies reporting navigation performance metrics from UAM demonstration flights.

Unlike conventional fixed-wing operations, future UAM vehicles are expected to operate within constrained urban corridors containing complex route geometries and frequent turning operations. In such environments, maintaining accurate flight-path tracking during turning segments becomes particularly important because lateral deviations can directly affect procedural separation and corridor capacity. Furthermore, future UAM operations are expected to involve heterogeneous eVTOL configurations that may exhibit different flight-path tracking characteristics depending on their flight control architecture and maneuvering capability. From an airspace design perspective, RNP values should not only satisfy navigation system performance requirements but also reflect the actual flight-path tracking performance demonstrated during flight operations. Therefore, empirical estimation of Total System Error (TSE) using real flight demonstration data can provide valuable reference information for establishing reasonable RNP design criteria for future urban UAM corridors. Particular attention is given to turning-flight segments because turning operations often represent the most challenging condition for maintaining accurate flight-path tracking.

This study utilizes OPPAV flight data obtained from the demonstration flights conducted in both non-urban and urban operational environments. The flight trajectories are classified into straight and turning segments, and tracking performance is analyzed using the statistical characteristics of FTE, including mean and standard deviation. Furthermore, Total System Error (TSE) is computed by incorporating FTE and Navigation System Error (NSE). Based on the analysis results, segment-wise RNP requirement levels applicable to urban UAM demonstration operations are proposed.

The results provide quantitative reference data that may support the development of navigation-performance requirements for future heterogeneous UAM operations.

2. Non-Urban Demonstration Analysis

2.1 Flight Data and Demonstration Overview

The analysis was conducted using telemetry data acquired during an OPPAV demonstration flight conducted under representative non-urban operational conditions. Figure 1 shows the OPPAV aircraft used during the demonstration.



Figure 1 – OPPAV aircraft

The analyzed dataset consisted of flight telemetry parameters including position, altitude, ground speed, heading, and timestamp information collected during the non-urban demonstration flight. The flight was conducted in a controlled test environment following predefined waypoint-based flight procedures representative of future UAM corridor operations.

The collected telemetry data were utilized to analyze trajectory characteristics and navigation performance during the flight operation.

2.2 Segment Classification and FTE Computation

To evaluate navigation performance under different operational conditions, the demonstration trajectory was divided into straight-flight and turning-flight segments based on waypoint transitions and heading variation characteristics. Figure 2 illustrates the overall flight trajectory and the classification of straight and turning segments used in this study.

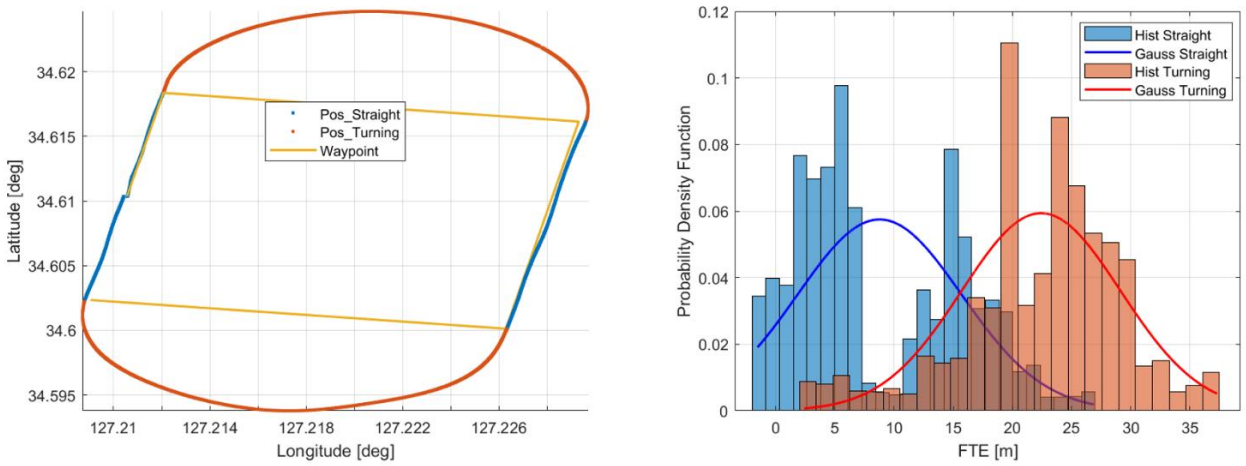


Figure 2 – Non-urban flight trajectory and segment classification

Flight Technical Error (FTE) was defined as the lateral cross-track deviation between the recorded flight trajectory and the reference flight path. For straight-flight segments, the reference path was defined as a line connecting adjacent waypoints. For turning-flight segments, the reference path was modeled as a circular arc defined by a predetermined turn center and radius.

Figure 2 also presents the FTE distributions for straight-flight and turning-flight segments. Gaussian fitting was applied to compare the statistical characteristics of the two operational conditions.

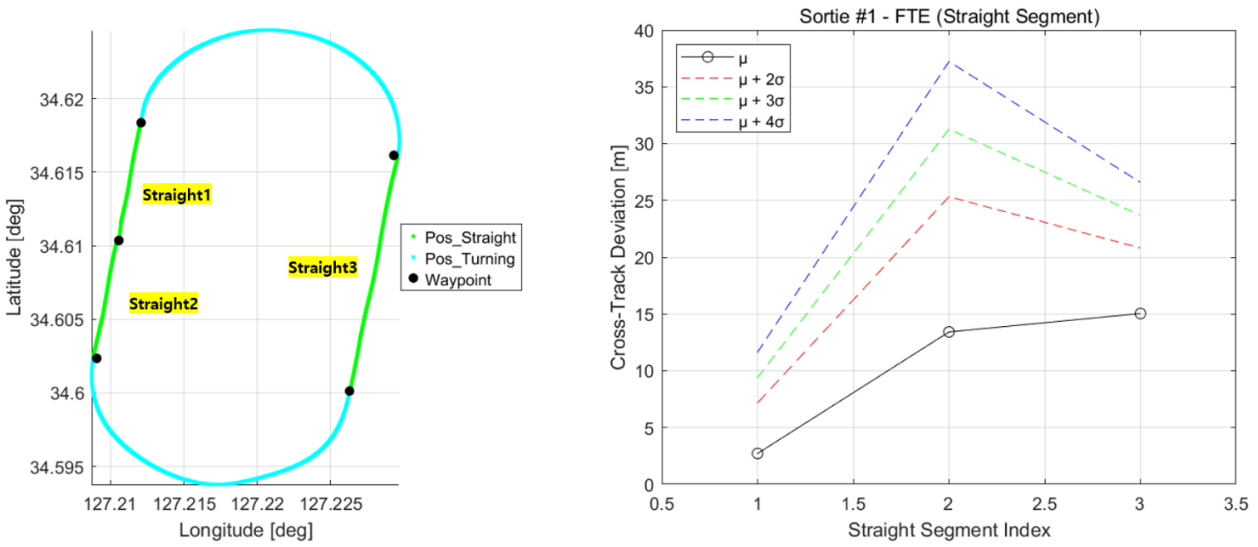


Figure 3 – FTE characteristics of straight-flight segments

As shown in Figure 3, three straight-flight segments were identified along the demonstration route. For each segment, the mean and standard deviation of the cross-track deviation were calculated to

evaluate the variability of lateral navigation performance.

The statistical envelopes based on the mean and standard deviation were additionally compared among the straight-flight segments. These results provide a quantitative representation of lateral trajectory dispersion under straight-flight conditions. Differences in FTE characteristics among the segments were also observed depending on the local trajectory geometry and waypoint configuration.

These segment-wise analyses were subsequently used to compare navigation performance characteristics between straight-flight and turning-flight conditions.

Similarly, Figure 4 presents the statistical characteristics of the turning-flight segments. The mean and standard deviation of the cross-track deviation were calculated for each turning segment to compare navigation performance characteristics under turning-flight conditions.

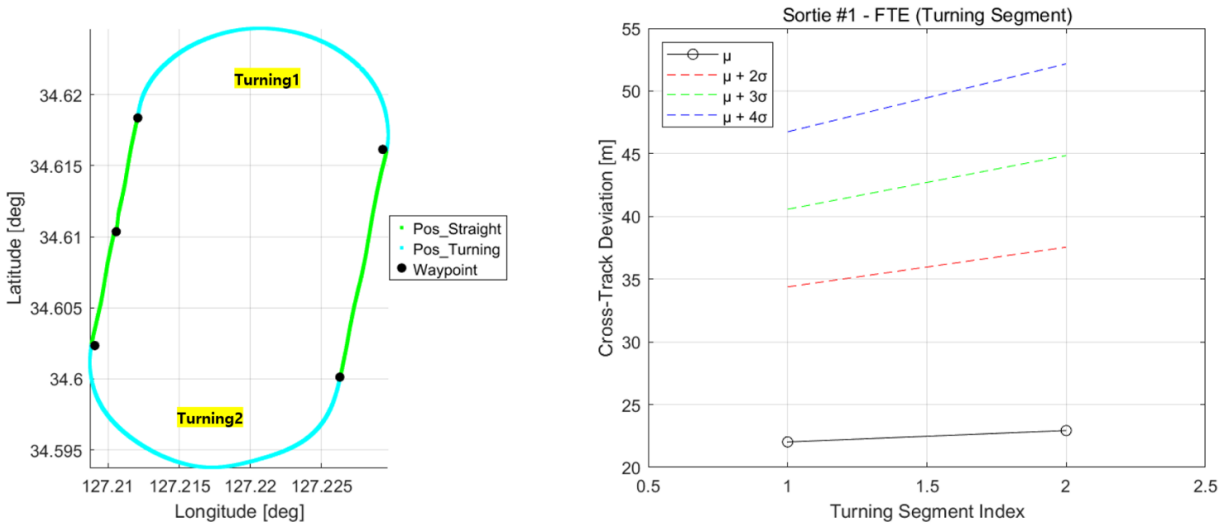


Figure 4 – FTE characteristics of turning-flight segments

2.3 Circle Fitting Analysis for Turning Segments

Circle fitting was performed to estimate the geometric characteristics of turning trajectories [8–10]. Figure 5 illustrates the circle fitting results for the turning-flight segments extracted from the demonstration trajectory. The red markers represent the recorded flight trajectory data during turning operations, while the blue circles indicate the estimated circular trajectories obtained through circle fitting. The blue cross markers denote the estimated circle centers derived from the flight data, whereas the black cross markers represent the reference turn centers defined in the planned flight path. The estimated circle parameters were subsequently analyzed to characterize the geometric properties of the turning-flight trajectories.

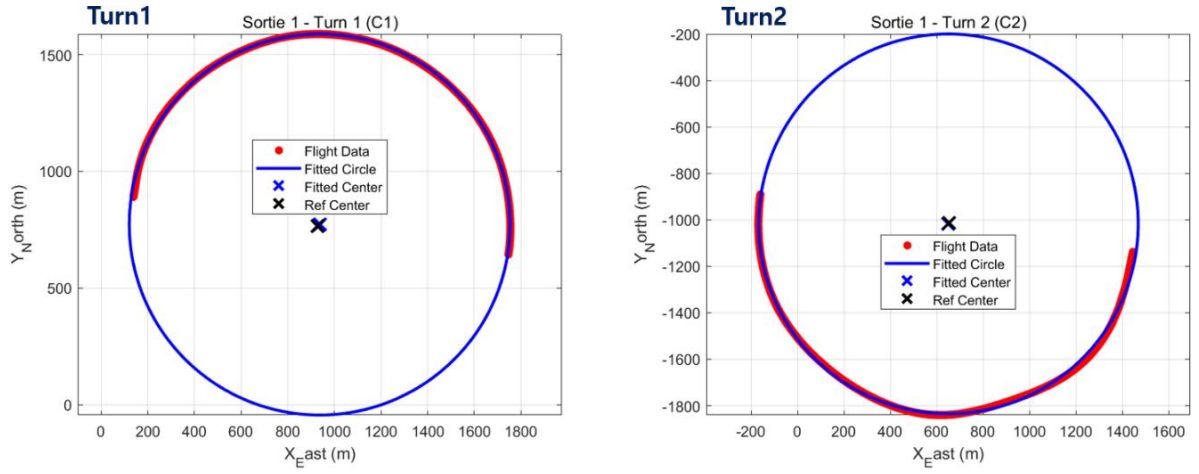


Figure 5 – Comparison of planned and estimated circles in turning segments

Table 1 summarizes the differences between the reference and estimated turn centers for the analyzed turning-flight segments. The estimated turn centers showed offsets of 9.713 m and 4.459 m for Turn 1 and Turn 2, respectively, with an average center difference of 7.086 m.

Table 1 – Difference between reference and estimated turn centers

Segment	Center offset
Turn1 (Ref. C1)	9.713 m
Turn2 (Ref. C2)	4.459 m

Table 2 compares the reference turning radii and the estimated radii obtained from the actual flight trajectories. The estimated turning radii were larger than the reference radii in both turning segments, with an average radius difference of approximately 19.48 m.

Table 2 – Comparison of reference and estimated turning radii

Segment	Reference radius	Estimated radius	Radius difference
Turn1 (Ref. C1)	798 m	816.843 m	+ 18.843 m
Turn2 (Ref. C2)	798 m	818.114 m	+ 20.114 m

2.4 TSE-Based RNP Requirement Estimation

TSE is defined as the root-sum-square (RSS) of FTE, NSE, and Path Definition Error (PDE) [1, 2], and is calculated as follows:

$$TSE = \sqrt{FTE^2 + NSE^2 + PDE^2}$$

Flight data were obtained using a NovAtel receiver supporting RTK and SBAS, providing RTK-level positioning accuracy. The mean (μ) and standard deviation (σ) of lateral trajectory deviations were estimated. Under the assumption of normality, the upper bound of FTE was defined as μ+2σ to approximate the 95% containment level. To characterize NSE, GNSS data collected over 48 hours in a static environment were post-processed to derive the NSE distribution characteristics under static conditions. Since the route designer and the aircraft use the same Geodetic Reference (WGS-84), PDE is virtually negligible (2). Accordingly, TSE was evaluated using FTE and NSE only. The resulting RNP requirement levels derived for OPPAV are summarized in Table 3.

Table 3 – Estimated RNP requirement levels for OPPAV

Segment	FTE (2σ, 95%)	NSE (2σ, 95%)	TSE (RNP)
Straight segment	0.0075 NM (13.89 m)	0.000027 NM (0.05 m)	0.0075 NM
Turning segment	0.0073 NM (13.52 m)		0.0073 NM

3. Urban Demonstration Analysis

3.1 Flight Data and Demonstration Overview

The analysis was conducted using telemetry data acquired during an OPPAV demonstration flight

conducted under representative urban operational conditions.

Figure 6 shows the OPPAV aircraft during the urban demonstration flight together with the corresponding flight trajectory. The demonstration involved waypoint-based flight operations designed to evaluate navigation performance in an urban operational environment.

The analyzed dataset consisted of telemetry parameters including position, altitude, ground speed, heading, and timestamp information recorded throughout the demonstration flight. The urban demonstration trajectory included both straight-flight and turning-flight operations under waypoint-based route conditions. These data were subsequently used to analyze segment-wise navigation performance characteristics in an urban operational environment.



Figure 6 – OPPAV urban demonstration flight and trajectory

3.2 Segment Classification and FTE Analysis

To analyze navigation performance characteristics in the urban operational environment, the demonstration trajectory was divided into straight-flight and turning-flight segments based on waypoint transitions and heading variation characteristics. Figure 7 illustrates the overall urban flight trajectory and the classification of straight and turning segments used in this study.

Flight Technical Error (FTE) was defined as the lateral cross-track deviation between the recorded flight trajectory and the reference flight path. Similar to the non-urban demonstration analysis, straight-flight segments were referenced using waypoint-connected linear paths, whereas turning-flight segments were modeled using predefined circular turning paths.

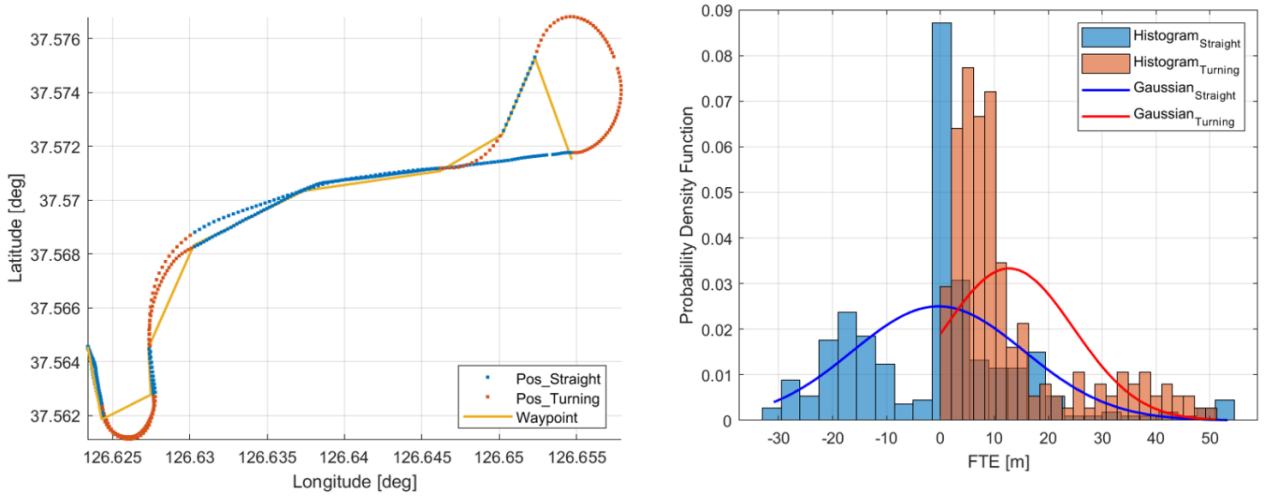


Figure 7 – Urban flight trajectory and segment classification

Figure 7 also presents the FTE distributions for straight-flight and turning-flight segments obtained during the urban demonstration flight. Gaussian fitting was applied to compare the statistical characteristics of trajectory deviations under urban operational conditions.

As shown in Figure 8, multiple straight-flight segments were identified along the urban demonstration trajectory. For each segment, the mean and standard deviation of the cross-track deviation were calculated to evaluate segment-wise navigation performance characteristics under urban operational conditions.

The statistical envelopes based on the mean and standard deviation were additionally compared among the straight-flight segments. Variations in FTE characteristics were observed depending on the local trajectory geometry and waypoint configuration within the urban operational environment.

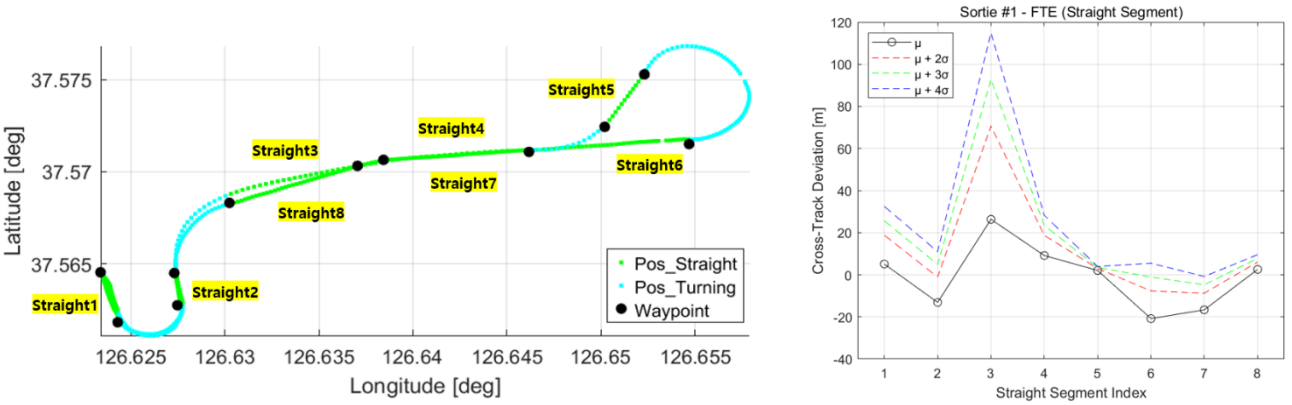


Figure 8 – FTE characteristics of urban straight-flight segments

As shown in Figure 9, multiple turning-flight segments were identified along the urban demonstration trajectory. For each segment, the mean and standard deviation of the cross-track deviation were calculated to evaluate navigation performance characteristics during turning-flight operations in the urban operational environment.

The statistical envelopes based on the mean and standard deviation were additionally compared among the turning-flight segments. Variations in FTE characteristics were observed depending on turning geometry and local waypoint configurations within the urban operational environment.

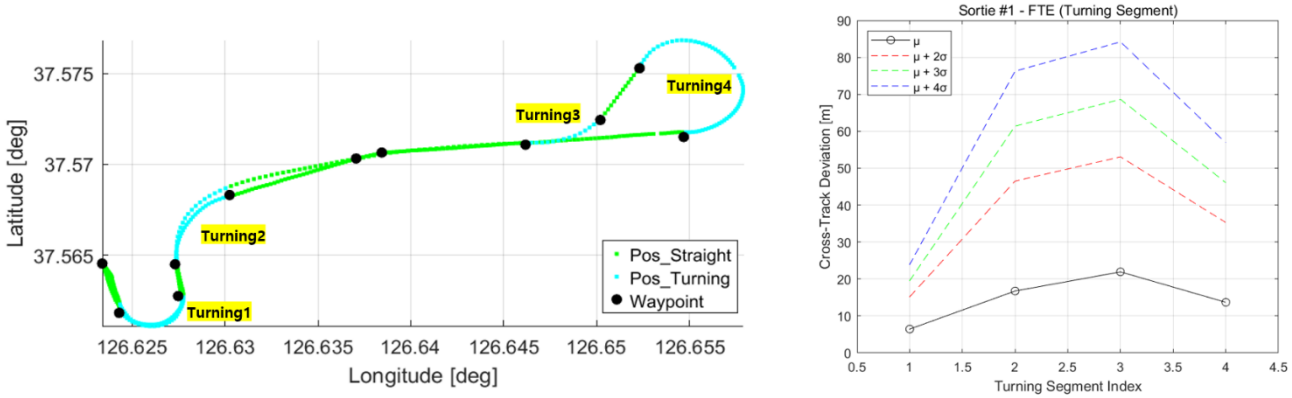


Figure 9 – FTE characteristics of urban turning-flight segments

3.3 Circle Fitting Analysis for Turning Segments

To analyze the geometric characteristics of turning-flight trajectories in the urban operational environment, circle fitting was performed using the recorded flight data extracted from the turning-flight segments. Figure 10 illustrates the fitted circular trajectories and estimated turn centers for the analyzed urban turning-flight segments. The red markers represent the recorded flight trajectory data during turning operations, while the blue circles indicate the estimated circular trajectories obtained through circle fitting. The blue cross markers denote the estimated circle centers derived from the flight data, whereas the black cross markers represent the reference turn centers defined in the planned flight path. Multiple turning-flight segments with different turning geometries were included in the urban demonstration trajectory.

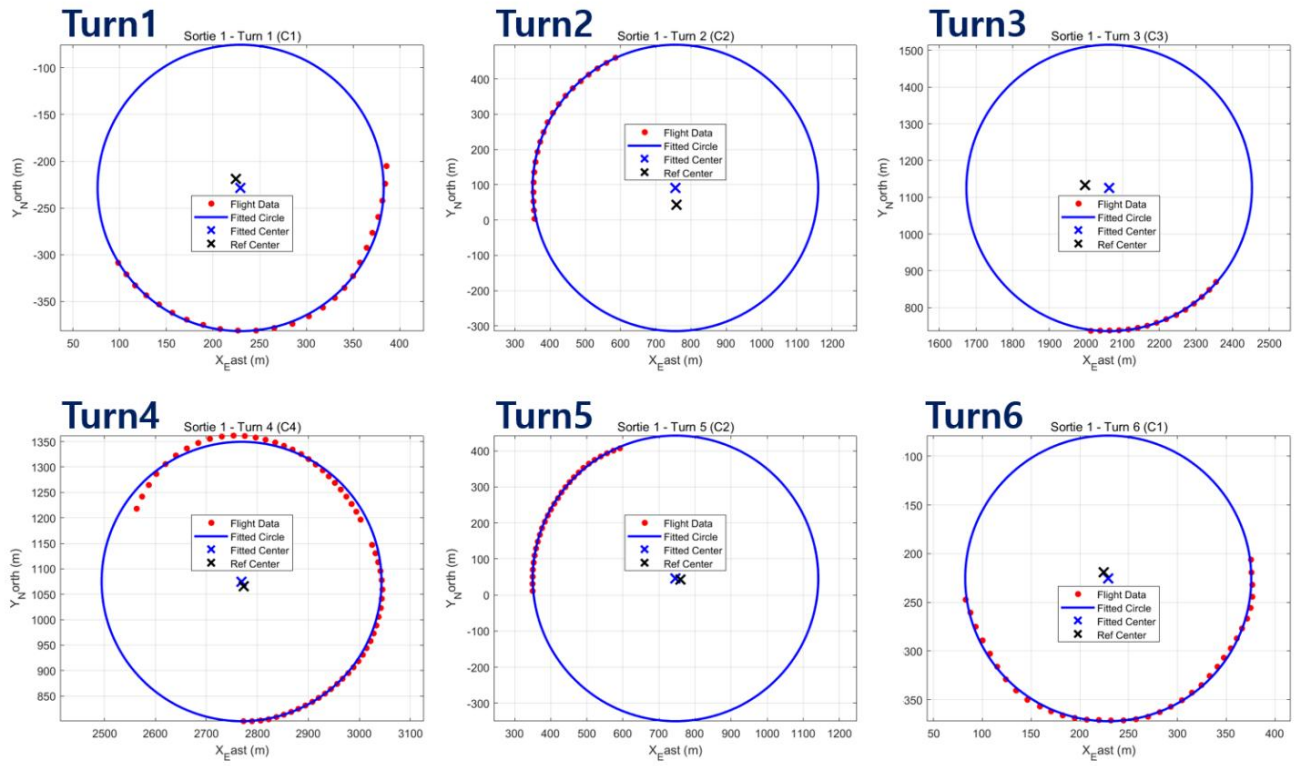


Figure 10 – Comparison of planned and estimated circles in urban turning segments

Table 4 summarizes the differences between the reference and estimated turn centers for the urban turning-flight segments analyzed in this study. The estimated turn centers showed varying offsets depending on the turning geometry, with an average center difference of approximately 26.03 m.

Table 4 – Difference between reference and estimated turn centers for urban turning segments

Segment	Center offset
Turn1 (Ref. C1)	10.8 m
Turn2 (Ref. C2)	47.77 m
Turn3 (Ref. C3)	65.88 m
Turn4 (Ref. C4)	10.35 m
Turn5 (Ref. C2)	13.40 m
Turn6 (Ref. C1)	8 m

Table 5 compares the reference turning radii and the estimated radii derived from the actual urban flight trajectories. The estimated turning radii showed both positive and negative deviations relative to the reference radii, with an average radius difference of approximately 6.82 m. These variations indicate that turning-flight trajectory characteristics can differ depending on local turning geometry and operational conditions within the urban environment.

Table 5 – Comparison of reference and estimated turning radii

Segment	Reference radius	Estimated radius	Radius difference
Turn1 (Ref. C1)	150 m	153.09 m	+ 3.09 m
Turn2 (Ref. C2)	400 m	405.42 m	+ 5.42 m
Turn3 (Ref. C3)	400 m	389.45 m	- 10.55 m
Turn4 (Ref. C4)	260 m	274.42 m	+ 14.42 m
Turn5 (Ref. C2)	400 m	395.95 m	- 4.05 m
Turn6 (Ref. C1)	150 m	146.62 m	- 3.38 m

3.4 TSE-Based RNP Requirement Estimation

Table 6 summarizes the estimated RNP requirement levels derived from the urban demonstration flight data. Similar to the non-urban demonstration analysis, NSE was negligible compared with FTE under the RTK GNSS environment.

The estimated TSE values corresponded to approximately 0.0172 NM for straight-flight segments and 0.0129 NM for turning-flight segments. These results indicate that navigation performance characteristics varied depending on flight segment geometry and operational conditions within the urban operational environment.

Table 6 – Estimated RNP requirement levels for OPPAV

Segment	FTE (2σ, 95%)	NSE (2σ, 95%)	TSE (RNP)
Straight segment	0.0172 NM (31.85 m)	0.000027 NM (0.05 m)	0.0172 NM
Turning segment	0.0129 NM (23.9 m)		0.0129 NM

4. Results and Discussion

This study analyzed segment-wise navigation performance characteristics using OPPAV demonstration flight data obtained from both non-urban and urban operational environments. The analysis results showed that FTE characteristics varied depending on flight segment geometry and operational conditions.

In the non-urban demonstration, relatively consistent trajectory tracking performance was observed across the analyzed flight segments. In contrast, the urban demonstration showed larger variations in trajectory characteristics due to more complex turning geometries and waypoint configurations. The circle fitting analysis additionally demonstrated differences between the planned and actual turning trajectories, particularly under urban operational conditions.

The TSE-based RNP estimation results indicated that NSE was negligible under the RTK GNSS environment, making FTE the dominant contributor to the estimated RNP levels. The estimated RNP

levels differed between straight-flight and turning-flight segments and also varied between non-urban and urban operational environments.

These findings suggest that segment-dependent navigation performance characteristics should be considered when establishing RNP requirements and operational design criteria for future UAM operations.

The observed differences between straight-flight and turning-flight segments suggest that flight-segment geometry should be considered when evaluating navigation performance and establishing RNP requirements for UAM operations. In particular, turning operations represent more demanding flight conditions for maintaining accurate flight-path tracking because aircraft must continuously follow curved reference paths. These results highlight the importance of incorporating actual flight-performance characteristics into future UAM airspace design and navigation requirement development. Consequently, empirically derived TSE information can support more flexible performance assessment approaches and provide quantitative guidance for future PBN-based UAM corridor design, particularly in urban areas with complex route geometries and maneuvering requirements.

5. Conclusions

This study estimated TSE-based RNP requirement levels for UAM demonstration operations using OPPAV flight data obtained from demonstration flights conducted under both non-urban and urban operational conditions. Segment-wise FTE characteristics were analyzed for straight-flight and turning-flight segments under both non-urban and urban operational environments.

The analysis results showed that navigation performance characteristics varied depending on flight-segment geometry and operational conditions. In the RTK GNSS environment considered in this study, NSE was negligible compared with FTE, indicating that FTE was the dominant factor affecting the estimated RNP levels. The estimated RNP levels also differed between flight-segment types and operational environments, demonstrating the influence of route geometry on flight-path tracking performance.

These findings suggest that navigation performance assessment for future UAM operations should consider segment-specific flight characteristics in addition to overall system performance. The use of empirical flight data provides a practical basis for establishing quantitative navigation performance requirements under operationally representative conditions.

The proposed TSE-based analysis framework can support future PBN-based UAM corridor design by providing quantitative reference data for RNP requirement development. Furthermore, the proposed framework may contribute to the development of performance-based airspace and corridor design concepts by providing quantitative navigation-performance references derived from actual flight operations.

From a practical perspective, the results of this study demonstrate the importance of evaluating navigation performance using actual flight demonstration data rather than relying solely on theoretical navigation specifications. This finding indicates that vehicle flight-path tracking capability plays a critical role in determining achievable navigation performance levels for future UAM operations.

Furthermore, the observed differences between straight-flight and turning-flight segments suggest that navigation performance may vary according to flight-segment geometry and operational environment. Such characteristics should be considered when developing future UAM operational procedures, corridor designs, and navigation performance requirements. The results therefore provide quantitative reference information that can support the establishment of realistic RNP criteria for UAM operations in both non-urban and urban environments.

Future work will focus on validating the proposed approach using additional flight datasets and establishing a verification framework for segment-dependent RNP evaluation in urban UAM operations. The results presented in this study may provide quantitative reference information for the development of performance-based UAM corridor design and navigation performance requirements for future eVTOL operations.

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