

Performance-Based Navigation and Airspace Safety in ASEAN: A Comparative Quantitative Analysis

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Abstract

This study aims to evaluate the impact of Performance-Based Navigation (PBN) implementation on airspace safety across ASEAN countries. Amid growing aviation traffic and the International Civil Aviation Organization (ICAO) push for harmonized air navigation strategies, ASEAN's PBN readiness varies significantly, warranting a regional assessment. Guided by the International Civil Aviation Organization (ICAO) Global Aviation Safety Plan (GASP) and Doc 9613 PBN Manual, this research investigates how integrating advanced navigation procedures and aligning policies contribute to improved safety outcomes. A comparative quantitative analysis was conducted using secondary data from 11 ASEAN countries between 2009 and 2023. Key variables include the PBN Coverage Index, Fleet RNAV Capability, Policy Alignment, and Safety Risk Index. Statistical methods included descriptive statistics, Pearson correlation, OLS regression, ANOVA, and hierarchical clustering. Regression results reveal that policy alignment with ICAO standards significantly reduces safety risk ($p < 0.05$), while higher PBN coverage shows a strong negative correlation with risk levels ($r = -0.80$). ANOVA indicates statistically significant differences in safety performance across readiness levels. Clustering analysis distinguishes three country groups, with Indonesia, Singapore, and Thailand leading in PBN readiness. The findings highlight the need for harmonized regional aviation strategies, particularly in countries with limited infrastructure, such as Timor-Leste. Strengthening regulatory compliance and technological adoption is essential for safety enhancement. This study offers integrated multi-method analysis of PBN implementation and safety outcomes in ASEAN, contributing empirical insights for aviation policymakers and ICAO stakeholders.

Keywords: Airspace safety, ASEAN, ICAO, performance-based navigation readiness.

Abstrak

Analisis Kuantitatif Komparatif Navigasi Berbasis Kinerja dan Keselamatan Ruang Udara di ASEAN: Penelitian ini bertujuan untuk mengevaluasi dampak implementasi Navigasi Berbasis Kinerja atau Performance-Based Navigation (PBN) terhadap keselamatan ruang udara di negara-negara ASEAN. Di tengah meningkatnya lalu lintas penerbangan serta dorongan dari ICAO untuk mewujudkan strategi navigasi udara yang terharmonisasi, tingkat kesiapan PBN di kawasan ASEAN menunjukkan variasi yang signifikan sehingga memerlukan penilaian pada tingkat regional. Berlandaskan Global Aviation Safety Plan (GASP) dan Performance-Based Navigation Manual (Doc 9613) yang diterbitkan oleh ICAO, penelitian ini mengkaji integrasi prosedur navigasi berbasis kinerja dan keselarasan kebijakan berkontribusi terhadap tingkat keselamatan penerbangan. Analisis kuantitatif komparatif dilakukan menggunakan data sekunder dari 11 negara di kawasan ASEAN periode 2009–2023. Variabel utama yang dianalisis meliputi PBN Coverage Index, Fleet RNAV Capability, Policy Alignment, dan Safety Risk Index. Metode statistik yang digunakan mencakup statistik deskriptif, korelasi Pearson, regresi Ordinary Least Squares (OLS), Analysis of Variance (ANOVA), serta analisis kluster hierarkis. Hasil regresi menunjukkan bahwa keselarasan kebijakan dengan standar ICAO secara signifikan menurunkan tingkat risiko keselamatan ($p < 0,05$), sementara tingkat cakupan PBN yang lebih tinggi menunjukkan korelasi negatif yang kuat dengan tingkat risiko ($r = -0,80$). Hasil ANOVA mengindikasikan adanya perbedaan yang signifikan secara statistik dalam kinerja keselamatan antartingkat kesiapan. Analisis kluster membedakan tiga kelompok negara, Indonesia, Singapura, dan Thailand berada pada posisi terdepan dalam kesiapan PBN. Temuan penelitian ini menegaskan perlunya strategi penerbangan regional yang terharmonisasi, khususnya di negara-negara dengan keterbatasan infrastruktur seperti Timor-Leste. Penguatan kepatuhan regulasi dan adopsi teknologi menjadi hal esensial untuk meningkatkan keselamatan penerbangan. Penelitian ini menawarkan analisis terpadu berbasis multi-metode pertama mengenai implementasi PBN dan hasil keselamatan penerbangan di kawasan ASEAN, serta memberikan kontribusi empiris bagi perumus kebijakan penerbangan dan pemangku kepentingan ICAO.

Kata Kunci: ASEAN, ICAO, keselamatan ruang udara, kesiapan navigasi berbasis kinerja.

1. Introduction

Performance-Based Navigation (PBN) has become a strategic pillar in modern air traffic management reform. Empirical evidence indicates that RNAV and RNP procedures significantly reduce route dispersion, improve trajectory predictability, and decrease airborne holding time, thereby enhancing operational efficiency in terminal airspace environments [1][2]. Quantitative assessments in high-density terminal airspace demonstrate measurable improvements in sequencing stability and airspace utilization following structured RNAV implementation [1]. In mature aviation systems, systematic PBN deployment has been associated with increased throughput capacity while preserving established safety margins [3]. The integration of optimized arrival and departure procedures has also been shown to reduce track miles, fuel burn, and exposure to emissions [4]. Beyond localized airport benefits, network-level analyses suggest that satellite-based navigation improves delay resilience under congestion, particularly in complex traffic networks [5]. Collectively, these findings support the operational advantages of PBN in high-density traffic environments. However, most empirical evidence originates from aviation systems characterized by advanced technological infrastructure, strong regulatory oversight, and institutional stability. The applicability of these findings to heterogeneous, developing multi-state regions remains insufficiently examined.

Beyond technical deployment, institutional alignment with international regulatory standards is increasingly recognized as a critical determinant of aviation safety performance. Empirical research demonstrates that governance quality and regulatory harmonization are significantly associated with improved safety outcomes and reduced systemic risk exposure [6]. Within the Safety Management System (SMS) framework, policy coherence, standardized oversight procedures, and compliance enforcement play a central role in reducing accidents and incidents [7]. Institutional fragmentation, by contrast, may generate procedural inconsistencies, reporting gaps, and uneven safety baselines across states. In multi-state regions such as ASEAN, disparities in regulatory adoption and implementation capacity may amplify cross-border operational vulnerabilities. Despite this theoretical linkage, few empirical studies have quantitatively tested the relationship between regulatory alignment and measurable safety risk indices at the regional scale.

In Asia, research on Performance-Based Navigation (PBN) has predominantly concentrated on single-country case studies. Empirical investigations in China demonstrate that RNAV implementation in terminal airspace yields measurable efficiency gains, while studies in Japan show that RNP-AR deployment enhances operational precision but also reveals procedural and regulatory challenges during implementation [8]. Although these contributions provide valuable technical and operational insights, they remain limited in scope. Specifically, they do not address structural divergence across multiple states operating within a shared regional airspace system, where institutional capacity, technological readiness, and governance structures vary significantly. Moreover, prior research largely relies on descriptive statistics, technical performance evaluations, or qualitative policy assessments. Few studies attempt to integrate infrastructure deployment, fleet modernization, and regulatory alignment into a unified comparative analytical framework. As a result, the literature lacks a comprehensive benchmarking model capable of simultaneously evaluating PBN coverage, RNAV fleet capability, institutional policy alignment, and quantified safety risk exposure. Importantly, no existing study combines these dimensions within a multi-method statistical design incorporating correlation analysis, regression modeling, variance testing, and clustering techniques to validate structural differentiation across states. This methodological gap is particularly critical in heterogeneous regions such as ASEAN, where disparities in governance capacity, infrastructure maturity, and fleet modernization levels create uneven safety baselines. Without an integrated quantitative benchmarking approach, it remains difficult to systematically assess how variations in PBN readiness translate into measurable differences in safety risk exposure across countries. Consequently, the absence of a structured comparative framework limits policymakers' ability to design evidence-based regional harmonization strategies aligned with ICAO modernization agendas.

2. Methodology

2.1. Research Design

The research design adopted in this study is cross-sectional, employing a country-level comparative framework based on observational secondary data from 11 ASEAN-region states. Cross-country quantitative designs are widely applied in transport systems and aviation safety research where controlled experimentation is infeasible and policy evaluation depends on structured administrative datasets [2][5]. Such comparative frameworks enable the identification of structural performance differentials across heterogeneous governance systems and airspace environments [9]. This study is non-experimental and analytical using numerical indicators to represent PBN implementation, institutional policy alignment, and quantified airspace safety outcomes. In aviation governance literature, observational comparative approaches are frequently used to assess regulatory effectiveness and safety performance under varying institutional conditions [6][7]. Empirical findings suggest that governance quality and infrastructure modernization can be meaningfully analyzed using macro-level comparative data despite limited sample sizes [10]. Given the relatively small sample size ($n = 11$), the use of Ordinary Least Squares (OLS) regression in this study is explicitly exploratory. Small- n regression modeling is considered appropriate when the objective is diagnostic inference, effect-size estimation, and hypothesis refinement rather than strict causal generalization [11][12]. In applied transport research, exploratory regression frameworks are commonly adopted when data availability is structurally constrained, yet theoretical expectations guide model specification [1].

Recent methodological studies emphasize that statistical inference in small samples should be interpreted alongside substantive effect magnitudes and robustness triangulation rather than relying exclusively on significance thresholds [13][14]. Furthermore, cross-sectional comparative modeling has been widely used in aviation network and safety performance research to detect structural divergence patterns across national systems [15][16]. To mitigate limitations associated with small-sample regression, the OLS findings are interpreted in conjunction with complementary analytical techniques, including Pearson correlation analysis, one-way ANOVA, and hierarchical clustering. Multi-method triangulation enhances internal consistency, reduces single-model dependency, and improves structural interpretability in governance-oriented quantitative research [17][18]. Accordingly, the research framework (Figure 1) emphasizes benchmarking and diagnostic evaluation rather than deterministic causality, aligning with contemporary comparative policy modeling in heterogeneous aviation regions.

2.2. Data and Sources

This study analyzes secondary data from 11 ASEAN-region countries, comprising the ten ASEAN member states and Timor-Leste as an associated regional state. Timor-Leste is included due to its geographical integration within ASEAN airspace and its interaction with regional air navigation systems. The unit of analysis is the country level ($n = 11$), covering 2009 to 2023 periods. Data sources include ICAO statistical databases, ASEAN Statistical Yearbooks, and national aviation policy documents.

2.3. Construction of Composite Indices

2.3.1. PBN Coverage Index

The PBN Coverage Index is developed as a composite measure capturing the scale of PBN infrastructure deployment at the national level. It combines three components: 1) Number of PBN-implemented airports; 2) Total RNAV route network; 3) Availability of RNP approach procedures.

This structure provides an integrated representation of both en-route and terminal PBN capabilities within each country. To ensure comparability across countries with different aviation scales, each component is normalized using min-max normalization:

$$X_{norm} = (X_i - X_{min}) / (X_{max} - X_{min}) \quad (1)$$

The PBN Coverage Index for country i is calculated as:

$$PBN\ Coverage\ Index_i = \frac{1}{3} (Airports_{norm,i} + RNAV\ Routes_{norm,i} + RNP\ Approaches_{norm,i}) \quad (2)$$

Equal weighting is applied to avoid subjective prioritization and to reflect ICAO principle that airports, routes, and approach procedures constitute complementary components of PBN implementation. This parsimonious weighting approach is consistent with established composite index construction methods in exploratory comparative research [13].

2.3.2. Safety Risk Index

The Safety Risk Index measures relative airspace safety exposure across countries by integrating operational safety indicators derived from open aviation datasets. It combines: 1) Number of reported air incidents; 2) Volume of NOTAMs issued; 3) Passenger traffic volume (as normalization control).

Incident-related variables are standardized per unit of traffic to control for differences in activity scale. All components are then normalized using min–max scaling.

The composite Safety Risk Index is expressed as:

$$\text{Safety Risk Index}_i = \frac{1}{k} \sum_{j=1}^k Z_{ij} \quad (3)$$

where Z_{ij} represents the normalized value of each safety-related indicator for country i , and k denotes the number of included indicators.

Higher index values indicate relatively higher safety risk exposure. Equal weighting is applied to maintain transparency and methodological neutrality, consistent with exploratory aviation safety assessment practices [14][15].

2.4. Data Processing and Analysis Techniques

Ordinary Least Squares (OLS) regression is employed to examine the association between three PBN readiness indicators—PBN Coverage Index, Fleet RNAV Capability, and Policy Alignment—and the Safety Risk Index [16]. Given the limited sample size, regression coefficients are interpreted as indicative directional relationships rather than definitive causal effects. Statistical significance is complemented by effect-size interpretation and cross-validation with correlation, ANOVA, and clustering results. This integrated analytical strategy enables robust pattern identification while acknowledging statistical constraints inherent in small-n cross-country datasets [17].

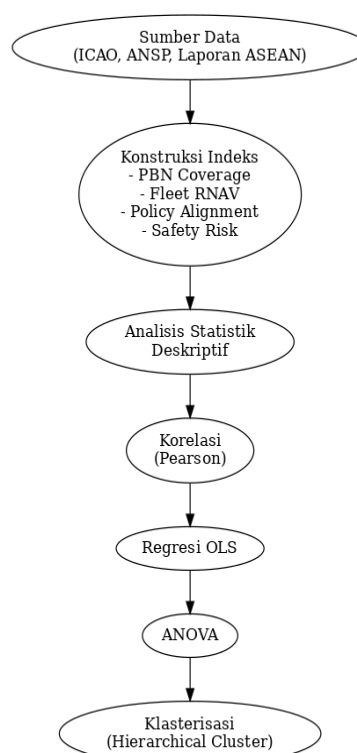


Figure 1. Flowchart of research methodology

2.5. Limitations of Methodology

Several methodological limitations should be acknowledged: 1) First, the small sample size ($n = 11$) limits statistical power and generalizability beyond the observed countries; 2) Second, cross-country variation in incident and NOTAM reporting standards may introduce measurement inconsistencies; 3) Third, the cross-sectional design precludes temporal and causal inference.

Accordingly, the findings should be interpreted as exploratory and diagnostic, serving as a foundation for future panel-based or longitudinal research incorporating human factors, AVSEC capacity indicators, and advanced predictive modeling techniques [18].

3. Results and Discussion

3.1. Descriptive Results and Key Findings

The descriptive analysis reveals significant variation in Performance-Based Navigation (PBN) readiness and airspace safety across ASEAN countries. As shown in Table 1, Indonesia recorded the highest PBN Coverage Index (70), followed by Thailand (52) and Malaysia (40), while Timor-Leste had the lowest (3). The average Safety Risk Index across countries was 4.85, with Timor-Leste exhibiting the highest risk (12.0) and Indonesia the lowest (1.74).

Table 1 presents descriptive statistics summarizing the implementation of Performance-Based Navigation (PBN) and airspace safety indicators across 11 ASEAN countries. The data reveal substantial variation in PBN infrastructure and operational conditions. On average, each country has implemented PBN procedures in 13 airports, with approximately 6.7 RNAV routes and 7.6 RNP approaches. The highest number of PBN-implemented airports is 35, while the lowest is 1, reflecting a wide disparity in infrastructure development. Similarly, Fleet RNAV Capability averages at 70.2%, ranging from 40% to 95%, indicating technological gaps in some member states. Passenger volume varies significantly, with a mean of 77.5 million, peaking at 250 million (Indonesia) and falling to 0.5 million (Timor-Leste). Reported air incidents average 13 per country, while NOTAM issuance—a proxy for airspace activity and regulatory communication—averages 158.5, reaching as high as 400.

The average PBN Policy Alignment score is 0.86, indicating that while some states fully align with ICAO standards, others lag behind. The PBN Coverage Index (combined measure of airports, RNAV routes, and RNP approaches) averages 27.4, with a maximum of 70. Finally, the Safety Risk Index averages 4.85, highlighting notable safety gaps between countries, with Timor-Leste recording the highest risk level (12.0) and Indonesia the lowest (1.74). Furthermore, the Pearson correlation matrix (Figure 2) demonstrates strong negative correlations between key PBN implementation indicators and the Safety Risk Index: the PBN Coverage Index ($r = -0.797$, $p = 0.0033$), Fleet RNAV Capability ($r = -0.926$, $p < 0.0001$), and Policy Alignment ($r = -0.973$, $p < 0.0001$). These findings suggest that greater alignment

Table 1. Descriptive statistics of PBN implementation and airspace safety in ASEAN

Variable	Mean	Std Dev	Minimum	Maximum	N
PBN_Implemented_Airports	13.0000000	11.1803399	1.0000000	35.0000000	11
RNAV_Routes	6.7272727	4.6279782	1.0000000	15.0000000	11
RNP_Approaches	7.6363636	6.5003496	1.0000000	20.0000000	11
DME_Stations	12.5454545	8.9371543	1.0000000	30.0000000	11
Fleet_RNAV_Capable	70.1818182	15.7912519	40.0000000	95.0000000	11
Passenger_Traffic_Million	77.5000000	83.0153600	0.5000000	250.0000000	11
Air_Incidents_Reported	13.0000000	11.7217746	1.0000000	35.0000000	11
NOTAM_Issued	158.5454545	138.0777778	5.0000000	400.0000000	11
Implementation_Year_Start	2012.45	3.6705214	2009.00	2022.00	11
Implementation_Year_End	2022.18	1.6011360	2020.00	2025.00	11
PBN_Policy_Alignment	0.8636364	0.1674678	0.5000000	1.0000000	11
PBN_Coverage_Index	27.3636364	22.1868102	3.0000000	70.0000000	11
Safety_Risk_Index	4.8508815	3.3981206	1.7400000	12.0000000	11

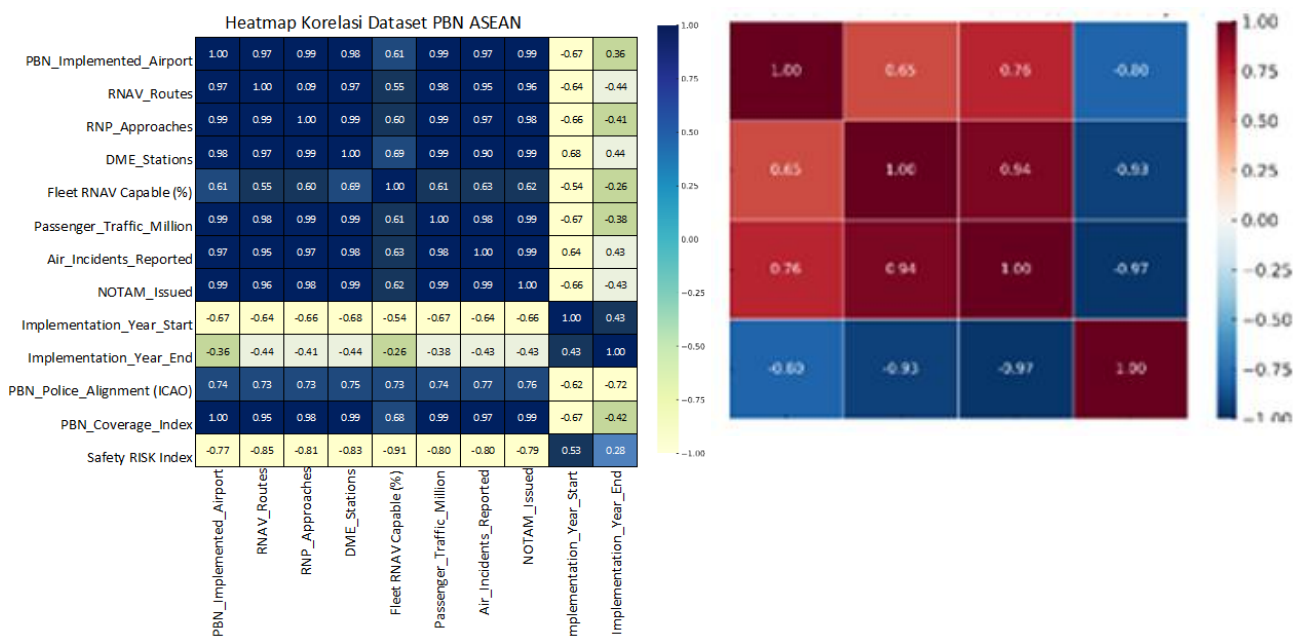


Figure 2. Correlation between PBN variables and safety risk index

with PBN standards is associated with lower levels of airspace safety risk. These findings also support the hypothesis that higher PBN readiness correlates with improved safety outcomes.

Figure 2 shows the Pearson correlation heatmap between four key variables: PBN Coverage Index, Fleet RNAV Capability, PBN Policy Alignment, and Safety Risk Index. Red indicates a strong negative correlation, while blue indicates a positive correlation. The results showed that the PBN Policy Alignment had the strongest negative correlation with air safety risks ($r = -0.973$), followed by Fleet RNAV Capability ($r = -0.926$) and PBN Coverage Index ($r = -0.797$). The positive correlation between PBN readiness indicators is also significant, indicating that good infrastructure accompanied by fleet readiness and policy compliance, results in improved airspace safety in ASEAN.

Figure 3 illustrates a visual comparison of the *PBN Coverage Index* across 11 ASEAN countries, reflecting the readiness of performance-based navigation infrastructure (PBN). This index is calculated from the number of airports that adopt RNAV and RNP procedures. Indonesia occupies the highest position (70), followed by Thailand (52), the Philippines (42), and Malaysia (40), indicating ICAO strong infrastructure and compliance. In contrast, Timor-Leste (3), Brunei (5), and Lao PDR (8) show low coverage due to limited infrastructure and regulations. Middle-tier countries such as Myanmar (18) and Singapore (15) show opportunities for expansion. This image confirms the relationship between high PBN coverage and lower safety risks.

Figure 4 presents a comprehensive visual comparison of PBN readiness and infrastructure in ASEAN countries through radar charts. Each line shows a country's standardized performance in key indicators: the number of PBN airports, RNAV routes, RNP approaches, DME stations, fleet RNAV capabilities, and policy alignment with ICAO. Indonesia performed superior in all aspects, followed by Thailand, Malaysia, and the Philippines as the most mature implementers of PBN. In contrast, Timor-Leste, Brunei, and Lao PDR are in the deepest positions, reflecting major limitations. Middle-tier countries such as Vietnam and Myanmar have shown limited progress. These visuals are important for policy mapping and for validating cluster and regression analysis.

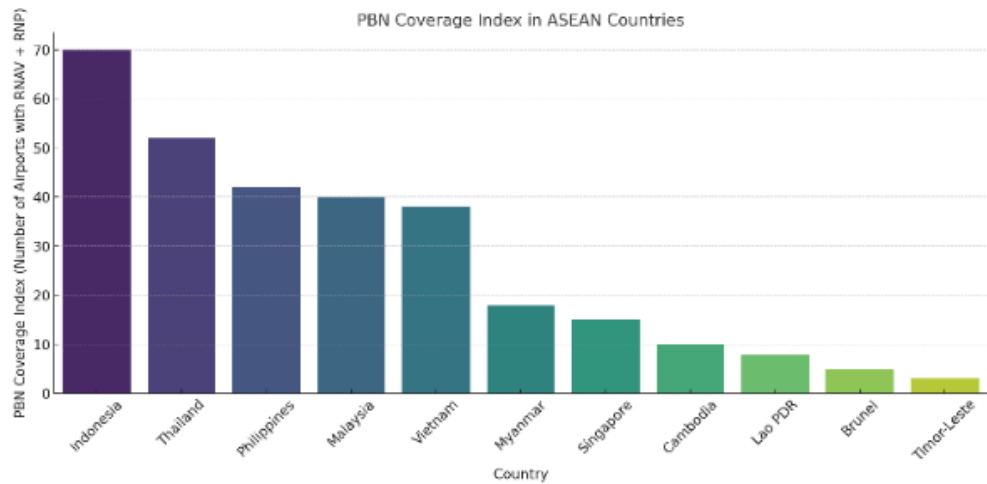


Figure 3. PBN coverage index in ASEAN countries

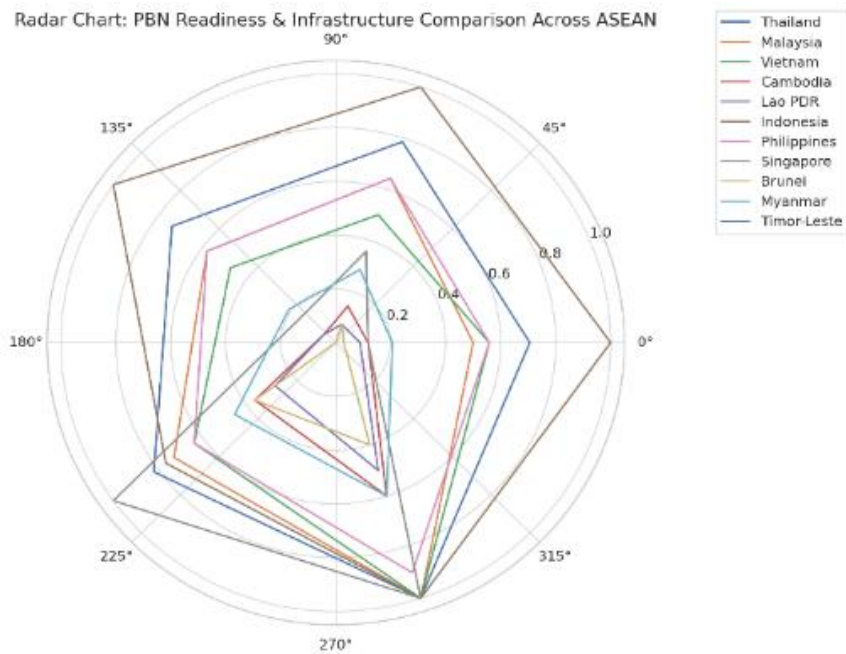


Figure 4. Radar chart PBN readiness & infrastructure comparison across ASEAN

3.2. Regression Analysis and Interpretation

OLS regression results (Table 2) show that the model explains 95.9% of the variation in the Safety Risk Index ($R^2 = 0.959$, $p < 0.0001$). Among the predictors, Policy Alignment with ICAO was the only statistically significant factor ($\beta = -13.53$, $p = 0.0403$), confirming its strong influence on safety outcomes. The negative coefficients for both PBN Coverage and Fleet Capability, while not individually statistically significant, suggest meaningful practical effects when combined.

Table 2 presents the results of the Ordinary Least Squares (OLS) regression analysis examining the effect of PBN implementation on the Safety Risk Index across ASEAN countries. The model includes three predictors: PBN Coverage Index, Fleet RNAV Capability, and PBN Policy Alignment, with a total of 11 observations. The overall model is statistically significant ($F(3,7) = 54.62$, $p < 0.0001$) and explains 95.9% of the variance in safety risk ($R^2 = 0.9590$, Adjusted $R^2 = 0.9415$). The low Root Mean Square Error (RMSE = 0.822) and Coefficient of Variation (16.95%) indicate a strong model fit and relatively low dispersion around the predicted values. Among the independent variables, only PBN Policy Alignment was statistically significant ($\beta = -13.54$, $p = 0.0403$), demonstrating a strong and negative effect on the Safety Risk Index. This means that a one-unit increase in policy alignment with ICAO standards is associated with a 13.5-point reduction in safety risk. While PBN Coverage Index and Fleet

RNAV Capability also showed negative coefficients, their p-values (0.238 and 0.412 respectively) indicate that their effects were not statistically significant at the 5% level. These results suggest that policy alignment is the most influential factor in reducing airspace safety risks, supporting ICAO emphasis on harmonized regulatory implementation under GASP.

Figure 5 illustrates the linear relationship between the *PBN Coverage Index* and the *Safety Risk Index* in 11 ASEAN countries through a scatter plot graph. Countries with high PBN coverage, such as Indonesia, Thailand, and Malaysia are shown at the bottom left of the graph, indicating a low level of safety risk. In contrast, Timor-Leste and Brunei occupy the top right positions with high risk and low coverage. The OLS regression line shows a negative, although not statistically significant, trend, indicating that increased PBN implementation tends to lower safety risks. These visual supports previous regression findings that policy alignment is the most significant factor in reducing risk.

Table 2. OLS regression: impact of PBN implementation on safety risk index

Variable	DF	ParameterEstimate	StandardError	t Value	Pr > t
Intercept	1	20.19465	1.84407	10.95	<.0001
PBN_Coverage_Index	1	-0.02428	0.01882	-1.29	0.2380
Fleet_RNAV_Capable	1	-0.04258	0.04884	-0.87	0.4122
PBN_Policy_Alignment	1	-13.53678	5.39093	-2.51	0.0403

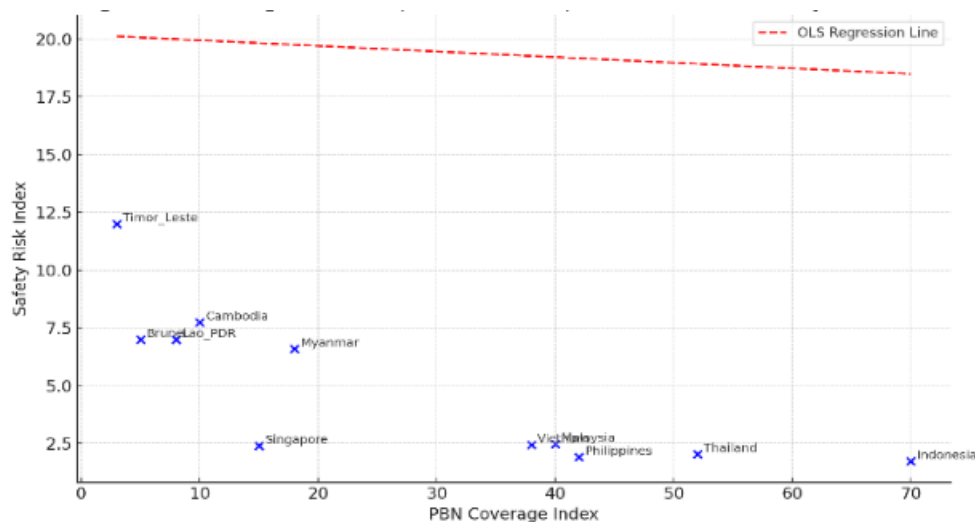


Figure 5. OLS regression: impact of PBN implementation on safety risk index

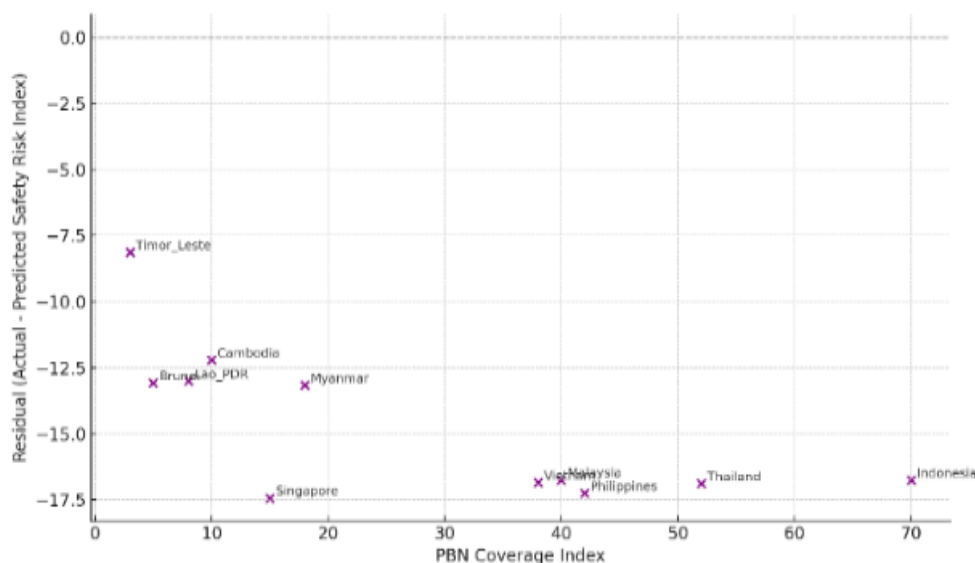


Figure 6. Residual by regressors for Safety Risk Index

Table 3. ANOVA: safety risk index differences by PBN readiness level

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Type	2	86.1895939	43.0947970	11.77	0.0041
Error	8	29.2826418	3.6603302		
Corrected Total	10	115.4722357			

Figure 6 shows a residual plot that illustrates the difference between the actual and predicted values of the *PBN Coverage Index*. A horizontal line of zero indicates the ideal predictive boundary. Most of the points lie near this line, indicating that the model's predictions are quite accurate and do not exhibit large bias. A small residual was found in countries with moderate to high PBN readiness, such as Indonesia and Malaysia, indicating a good model fit. In contrast, large residual emerges in Timor-Leste and Brunei, reflecting inaccurate predictions due to limited infrastructure. Overall, this plot confirms the validity of the linear model without violating the main regression assumption.

Figure 7 shows the scatter plot of the bivariate relationship between *the PBN Coverage Index* and *the Safety Risk Index* for 11 ASEAN countries. Each dot represents a country with a name label, indicating a clear negative trend—the higher the PBN coverage, the lower the air safety risk. Indonesia has the highest coverage index (70) and the lowest risk (1.74), while Timor-Leste is the opposite. Countries such as Thailand, Malaysia, and Vietnam congregate in areas of high coverage and low risk, signaling effective PBN integration. Brunei, Lao PDR, and Myanmar are in the middle. Although the regression line is not shown, the pattern of decline appears clear and supports previous statistical findings.

3.3. ANOVA and Cluster-Based Insights

The ANOVA test (Table 3) confirmed that safety performance differs significantly across readiness groups ($F(2,8) = 11.77, p = 0.0041$). Post hoc Tukey tests revealed that countries in the "Low" readiness group (e.g., Timor-Leste, Myanmar) had significantly higher safety risks than those in the "High" readiness groups (e.g., Indonesia, Thailand).

Table 3 presents the detailed output of the one-way ANOVA test, examining whether there are statistically significant differences in the Safety Risk Index among countries grouped by their PBN Readiness Level. The grouping was based on PBN Coverage Index thresholds: High (≥ 40), Medium (15–39), and Low (< 15). The ANOVA model shows a highly significant result with $F(2,8) = 11.77$ and $p = 0.0041$, indicating that at least one group mean differs significantly from the others. The model explains approximately 74.6% of the variance in safety risk scores ($R^2 = 0.7464$), suggesting a strong explanatory relationship between PBN readiness and airspace safety. The model's mean square value (43.09) is substantially higher than the error term's (3.66), reinforcing the conclusion that group differences are more pronounced than within-group variation. The coefficient of variation ($CV = 39.44\%$) and Root Mean Square Error (1.91) are acceptable for this type of policy-oriented cross-country analysis. These results strongly support the theoretical expectation that increased PBN readiness, as measured by infrastructure, capability, and policy alignment leads to measurable improvements in aviation safety outcomes. It also validates ICAO emphasis on PBN implementation as a key strategic target for global and regional aviation safety planning

Figure 8 presents a boxplot showing the difference in *Safety Risk Index* among the three PBN readiness groups: High, Medium, and Low. Countries in the High group such as Indonesia, Thailand, Malaysia, and Vietnam have the lowest safety risk (1.7–2.5) and are widely dispersed. In contrast, Low groups such as Timor-Leste, Brunei, and Lao PDR show the highest risk (7.0–12.0) with wide distribution. The Medium group is somewhere between the two with moderate risk. This visualization aligns with the ANOVA results ($p = 0.0041$), confirming that higher PBN readiness correlates with lower safety risks and supporting the urgency of PBN investment.

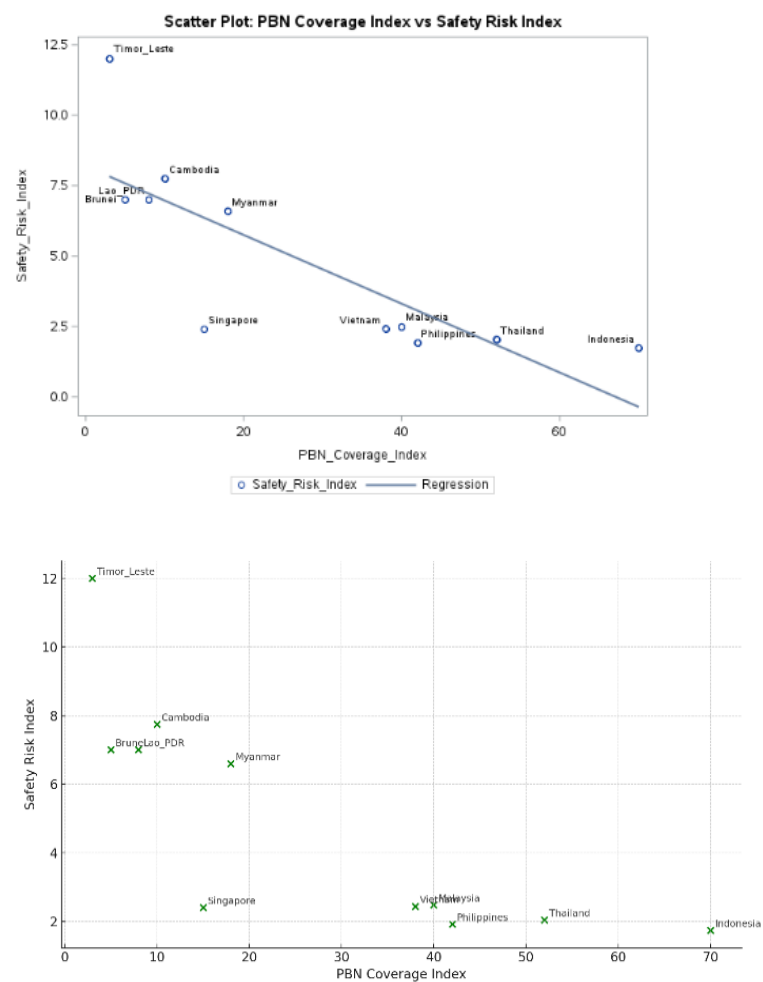


Figure 7. Scatter plot PBN coverage index vs safety risk index

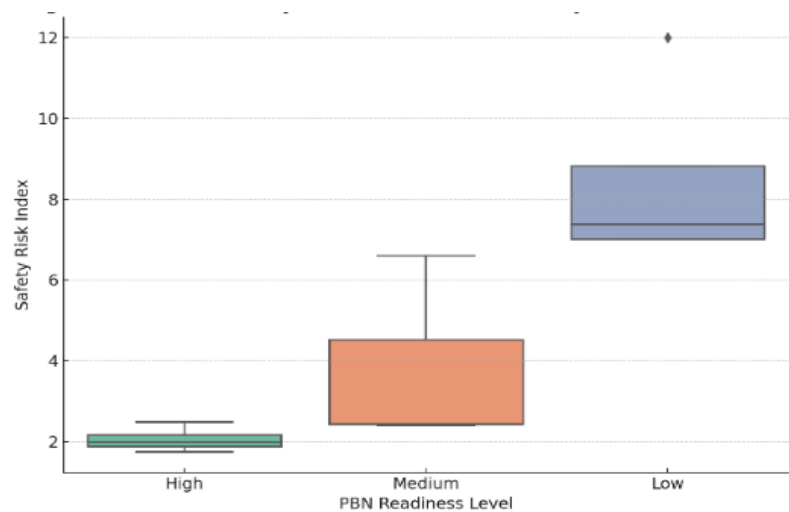


Figure 8. ANOVA: safety risk index differences by PBN readiness level

Figure 9 shows the *Safety Risk Index* boxplot based on three groups of PBN readiness: High, Medium, and Low, based on the *PBN Coverage Index*. Each box shows the interquartile range, median, and outliers, with jitter points showing the actual values for each country. High-readiness groups such as Indonesia, Thailand, and Malaysia show low and stable risk values. In contrast, the Low readiness group (Timor-Leste, Brunei, Lao PDR) showed high median and wide variation, indicating inconsistent safety conditions. The Medium readiness group is in the middle with overlap in both directions. This visualization confirms the ANOVA and Tukey test results, indicating significant differences between groups.

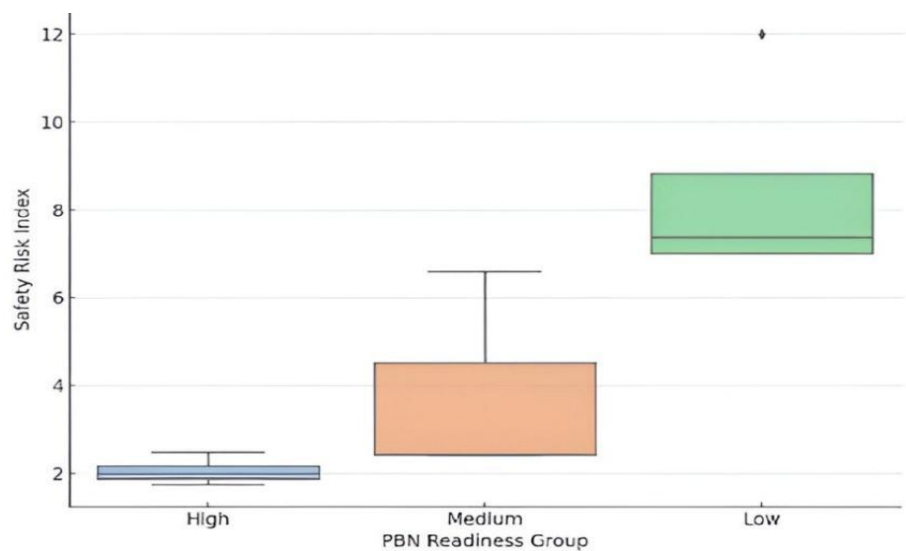


Figure 9. Boxplot safety risk index per PBN readiness group

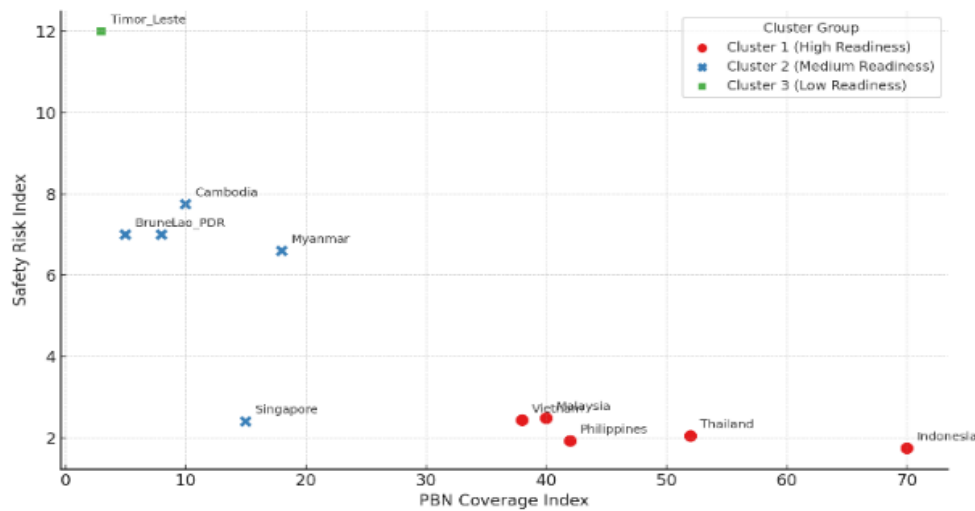


Figure 10. Cluster output 3 groups of ASEAN countries by PBN indicators

Figure 10 shows the final results of hierarchical clustering of 11 ASEAN countries based on *the PBN Coverage Index* and *Safety Risk Index*. Each point represents a country, assigned a color and based on its cluster. Cluster 1 (High Readiness) includes Indonesia, Thailand, Malaysia, Vietnam, Singapore, and the Philippines with high PBN infrastructure and low safety risks. Cluster 2 (Medium Readiness) includes Cambodia, Laos, Brunei, and Myanmar, which show moderate readiness. Cluster 3 consists only of isolated Timor-Leste with minimal infrastructure and the highest risk. This visualization supports statistical results and serves as a policy tool for allocating technical support and regional investment.

Table 4 presents the final results of the ASEAN country cluster membership based on a hierarchical analysis using the Ward method. Countries are grouped into three clusters based on the similarity of *the PBN Coverage Index*, *Fleet RNAV Capability*, and *Safety Risk Index*. Cluster 1 (CL3) comprises countries with high PBN readiness and low safety risks, including Malaysia, Vietnam, the Philippines, Thailand, Indonesia, and Singapore. Cluster 2 (CL5) includes countries with moderate readiness, namely Cambodia, Laos, Brunei, and Myanmar. Cluster 3 only includes Timor-Leste as an outlier. This classification is important for setting policy priorities, regional harmonization, and technical support.

Table 4. Cluster membership of ASEAN countries

Obs	Country	CLUSTER	CLUSNAME
1	Malaysia	1	CL3
2	Vietnam	1	CL3
3	Philippines	1	CL3
4	Thailand	1	CL3
5	Indonesia	1	CL3
6	Singapore	1	CL3
7	Cambodia	2	CL5
8	Lao_PDR	2	CL5
9	Brunei	2	CL5
10	Myanmar	2	CL5
11	Timor_Leste	3	Timor_Leste

3.4. Theoretical and Practical Implications

From a theoretical perspective, this study supports the GASP framework by empirically validating the link between policy alignment and safety outcomes. It extends prior research by integrating operational metrics with policy indicators across a developing region. Practically, the results highlight the importance of ICAO-aligned policy frameworks and fleet modernization in enhancing safety. Aviation authorities in lower-tier countries should prioritize regulatory compliance, training, and infrastructure investment to reduce safety disparities.

3.5. Comparison with Prior Literature

While previous studies, such as those by EUROCONTROL and FAA highlighted PBN's benefits in developed contexts, this research provides novel insight into its impact in emerging economies. The strong significance of policy alignment observed here contrasts with earlier works that emphasized technology alone.

3.6. Limitations and Recommendations for Future Research

This study is limited by its small sample size (n = 11) and cross-sectional design, which restricts causal inference. Variability in incident data across states may also affect reliability. Future studies should employ panel data or time-series regression to assess the impact of PBN longitudinally. In addition, integration of human resource indicators (e.g., ATC training, CBTA compliance) and predictive modeling via machine learning could enrich future analyses.

3.7. Policy and Technical Recommendations

The comparative findings of this study reveal that improving airspace safety in ASEAN cannot rely solely on statistical validation but requires concrete policy and technical actions. First, regional authorities under ICAO and ASEAN should harmonize regulatory frameworks and conduct periodic safety audits to ensure that national PBN policies consistently align with Doc 9613 and the Global Aviation Safety Plan (GASP). This harmonization will accelerate convergence among member states and reduce regulatory disparity.

Second, countries with lower readiness levels, such as Timor-Leste, Lao PDR, and Brunei, need to prioritize infrastructure investment for RNAV/RNP route expansion, navigational aids, and ground-based augmentation systems. At the same time, parallel programs for fleet modernization toward RNAV-capable aircraft must be initiated, particularly for national carriers and operators in high-density routes.

Third, enhancing human resource capacity remains a decisive factor. Competency-based training and assessment (CBTA) for air traffic controllers, flight procedure designers, and airline operators should be institutionalized through regional workshops and collaborative programs. This approach will narrow the operational expertise gap between advanced and emerging states.

Fourth, integrating data systems for incident reporting, NOTAM dissemination, and safety performance indicators is essential. A shared ASEAN platform would enable real-time monitoring, risk detection, and evidence-based decision-making to strengthen regional safety governance.

Finally, a progressive roadmap for PBN implementation is needed to guide states with different readiness levels. This roadmap should specify short-term objectives (≤ 3 years) focused on regulatory adoption, medium-term goals (3–6 years) on infrastructure expansion, and long-term targets (> 6 years) on fleet modernization and advanced safety monitoring. Such staged planning will ensure sustainable development and balanced regional safety enhancement.

4. Conclusion

This study aims to analyze the impact of implementing *Performance-Based Navigation* (PBN) on airspace safety in ASEAN countries. Using quantitative indicators such as *the PBN Coverage Index*, *Fleet RNAV Capability*, and *Policy Alignment to the Safety Risk Index*, this study fills gaps in the regional aviation literature. The analysis showed a strong statistically significant relationship between PBN readiness, particularly policy alignment with ICAO standards—and reduced safety risks. Countries with high readiness, such as Indonesia, Malaysia, and Singapore, show low risk scores, while countries with limited infrastructure, such as Timor-Leste, have the highest risk. Hierarchical cluster analysis groups countries in three clear levels of readiness.

These findings provide empirical validation for ICAO GASP framework and emphasize the importance of a harmonized regional navigation strategy. The practical implications include policy priorities, resource allocation, regional safety audits, and the development of a multi-level implementation roadmap. The limitations of this study include the cross-sectional design, the small sample size ($n=11$), and reliance on secondary data. Follow-up studies are suggested using long-term panel data, machine learning approaches to risk prediction, and the integration of qualitative data such as ATC training, pilot compliance, and weather influences to achieve more comprehensive outcomes.

The novelty of this study lies in integrating multi-method approaches (descriptive analysis, correlation, regression, ANOVA, and clustering) with composite indicators such as the PBN Coverage Index, Fleet RNAV Capability, Policy Alignment, and the Safety Risk Index in the ASEAN context. This cross-country approach has not been conducted previously, thereby offering an original contribution to the literature on regional airspace safety.

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