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Comparative Analysis of Marine Traffic Risk Assessment Practices and Navigational Risk in Three Malaysian Ports

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ABSTRACT

This exploratory cross-port study evaluates marine traffic exposure and fairway-geometry screening indicators at Port Klang, the Port of Tanjung Pelepas (PTP), and Penang Port. Secondary vessel-transit aggregates for August and September 2025 comprise 1,811, 743, and 429 movements, respectively. Following conversion of fairway areas from square kilometres to square nautical miles, mean monthly transit intensities are 1,411.72, 589.91, and 274.52 transits per $\mathbf{nm^2}$ per month. An obstacle-contact geometry index based on selected vessel beam, fairway width, and an algebraically inferred 5 m obstacle-width assumption yields 4.16%, 10.75%, and 24.50%. A second fairway length–width index yields 92.77%, 95.28%, and 99.05%. These dimensionless screening values are not empirically calibrated grounding or stranding probabilities. Port Klang exhibits the greatest movement exposure, whereas Penang Port exhibits the greatest geometric constraints under the selected vessel and fairway assumptions. The findings demonstrate the need to distinguish observed traffic activity from navigational geometry and to validate both against spatially explicit traffic, chart, and incident records before drawing conclusions about operational accident risk.

Keywords: marine traffic risk assessment; automatic identification system; fairway geometry; vessel transit intensity; navigational safety

1. Introduction

Maritime transport is fundamental to international trade, with more than 80% of merchandise trade by volume carried by sea (United Nations Conference on Trade and Development [UNCTAD], 2022). Malaysian ports, including Port Klang, the Port of Tanjung Pelepas (PTP), and Penang Port, support major domestic and international shipping activities. Vessel movements in port approaches occur within navigational corridors where vessel dimensions, traffic interactions, visibility, available sea room, and route geometry can constrain safe manoeuvring. Consequently, navigational risk assessment must consider both the extent of traffic exposure and the physical characteristics of the waterway (Bellsolà Olba et al., 2020; Chai et al., 2017).

Marine Traffic Risk Assessment (MTRA) involves identifying hazards, characterising vessel activity and relevant operating conditions, and evaluating their potential consequences. Automatic Identification System (AIS) records provide spatial and temporal information on vessel movements and have been used to examine traffic distributions in the Port Klang region and the Strait of Malacca (Mustaffa et al., 2016; Zaman et al., 2015). Nevertheless, a count of vessel transits or an area-normalised movement intensity is a measure of exposure, not an accident probability. Collision and grounding assessments require further information about encounter geometry, environmental and human factors, and empirically established relationships between hazards and incidents (Chen et al., 2019; Montewka et al., 2010).

Comparative assessments can be misleading when they use inconsistent time periods, spatial units, vessel selection procedures, or interpretations of risk equations. A narrow, elongated fairway may generate a high value under a geometry-based formula even when measured traffic volume is comparatively low. Conversely, a busy fairway may carry substantial movement exposure without presenting the same dimensional constraints. Earlier studies have emphasised the value of AIS analysis, explicit modelling assumptions, and multidimensional port-risk frameworks, but a direct numerical comparison must still ensure that its indicators have compatible meanings and documented inputs (Bellsolà Olba et al., 2020; Ramin et al., 2020).

This study examines three Malaysian port-fairway examples using two monthly vessel-transit aggregates and available fairway and vessel dimensions. Its objectives are to (1) compare recorded vessel movements and area-normalised movement intensity; (2) evaluate two reproducible fairway-geometry screening relationships under explicit assumptions; and (3) identify implications for more consistent and evidence-based MTRA practices. The study is a descriptive comparison of specified fairway configurations and does not estimate the overall safety performance of the ports.

2. Literature Review

2.1 AIS-Based Assessment of Marine Traffic

AIS datasets enable analysis of vessel routes, speed, traffic distribution, and vessel interactions. Tu et al. (2018) reviewed the use of AIS for maritime navigation applications, including anomaly detection, route estimation, and collision prediction. In the Malaysian context, Mustaffa et al. (2016) analysed a seven-day AIS observation window near Port Klang to investigate traffic patterns and vessel characteristics. Ramin et al. (2020) applied time-series and regression methods to traffic-density prediction in the Port Klang and Strait of Malacca region. These studies show the usefulness of clearly bounded traffic datasets while also demonstrating that findings are sensitive to the observation period and measurement method.

Traffic intensity based on transits per unit area is distinct from instantaneous vessel occupancy and encounter frequency. An area-normalised movement metric requires a consistently defined spatial boundary and a clear time basis. A vessel may cross a counting boundary more than once, and different sources may define a transit differently. Consequently, reported movement intensity can support descriptive comparison but cannot independently establish casualty incidence or collision likelihood (Lewison, 1978; Tu et al., 2018).

2.2 Marine Traffic Risk Models and Validation

Quantitative navigational-risk models range from geometric encounter descriptions to analyses incorporating casualty frequencies, human and organisational factors, and accident consequences. Lewison (1978) related potential vessel encounters in the Dover Strait to recorded collision outcomes. Montewka et al. (2010) proposed collision-probability modelling that incorporated traffic data and ship dynamics and compared model outputs with observed traffic. Chai et al. (2017) developed a quantitative collision-risk framework that accounted for accident frequencies and consequences. Chen et al. (2019) subsequently reviewed probabilistic collision-risk methods and highlighted methodological uncertainties, particularly those involving causation and human factors.

These approaches illustrate the difference between a geometric opportunity for an incident and a statistically calibrated event probability. A dimensionless ratio derived solely from vessel dimensions and fairway geometry may be useful for preliminary screening, but it requires assumptions, an applicable event definition, and validation before it can be interpreted as a probability. Foundational analyses of marine traffic accidents, including Fujii (1982), reinforce the importance of empirical accident records when studying navigational hazards; they do not by themselves validate the specific screening expressions evaluated in this paper.

2.3 Navigational Risk in Ports and Constrained Fairways

Port-specific studies increasingly integrate navigational conditions rather than relying on a single indicator. Bellsolà Olba et al. (2020) developed the Nautical Port Risk Index by incorporating multiple nautical-risk criteria and expert judgements into a structured port-risk assessment. Nguyen et al. (2015) examined AIS traffic distributions in the Strait of Malacca, while Zaman et al. (2015) used AIS-derived observations and a risk-matrix approach to evaluate navigation conditions. These studies provide a methodological context for comparing vessel activity, navigable space, and hazard exposure.

In constrained waterways, vessel beam relative to navigable width is a relevant geometric consideration. However, actual safe passage also depends on draught and under-keel clearance, tidal windows, traffic management, turning performance, aids to navigation, environmental conditions, and human decisions. Thus, geometry is one component of a comprehensive port-risk assessment, not a substitute for operationally validated safety metrics (Bellsolà Olba et al., 2020; Chen et al., 2019).

2.4 Research Focus

The literature supports transparent traffic measurement and multi-factor risk modelling, yet descriptive cross-port comparisons can still conflate traffic density with accident probability or assign probabilistic interpretations to uncalibrated geometric ratios. The present study addresses this analytical distinction by applying consistent area and time units to the available traffic aggregates and examining the implications of two dimensionless fairway screening indices. The resulting findings are intended to inform the design of more detailed local risk assessments, not to replace them.

3. Methodology

3.1 Research Design

An exploratory comparative case-study design was adopted for Port Klang, PTP, and Penang Port. The analysis combines secondary aggregated monthly vessel-transit figures with selected fairway dimensions and reference-vessel particulars for the August–September 2025 period. It involves descriptive arithmetic calculations rather than a fitted predictive model. No primary interviews, surveys, accident-history calibration, or independent hydrographic measurements form part of the analytical dataset.

The analytical sequence comprises identification of the three port-fairway cases; compilation of the available traffic and dimensional variables; unit standardisation and calculation of mean monthly movement intensity; evaluation of simplified geometric screening expressions; and cross-port comparison of the resulting indicators. The five-stage workflow is illustrated in Figure 1.

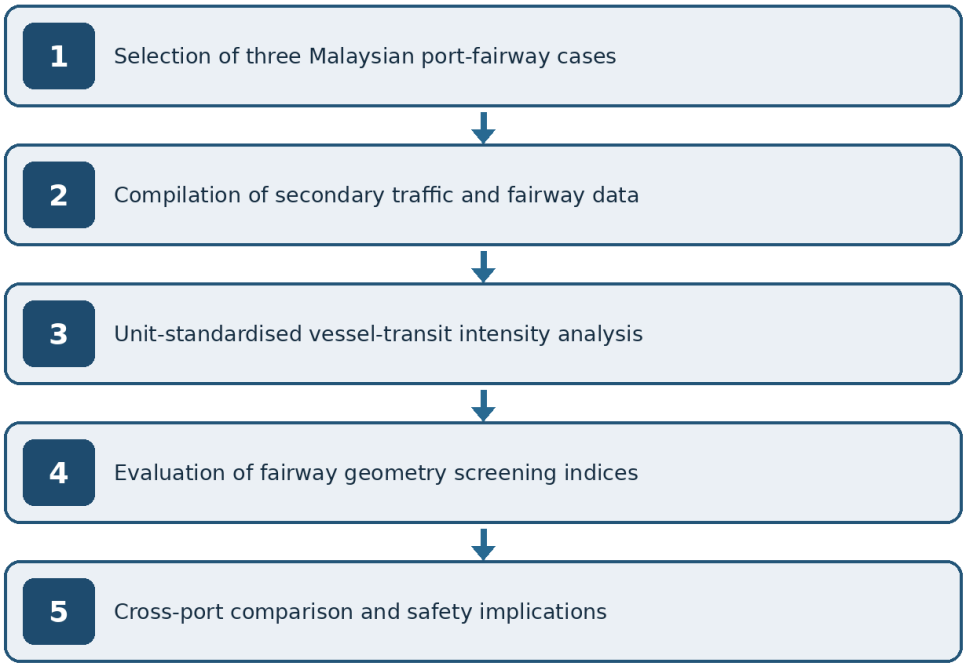


Figure 1. Five-stage study workflow for secondary traffic and fairway-geometry screening.

3.2 Selection of Port-Fairway Cases

The three sites were selected purposively to capture contrasting patterns of vessel movement and available fairway geometry. Port Klang is a major commercial port, PTP is a significant transshipment hub, and Penang Port accommodates mixed commercial and regional shipping activity. The analysis is restricted to the particular fairway dimensions and reference-vessel characteristics tabulated below; it does not assume that these inputs describe every channel or vessel operating within each port.

3.3 Variables and Secondary Data

The numerical dataset contains August and September 2025 vessel-transit totals, selected fairway lengths and widths, and one reference-vessel length overall (LOA) and beam for each port. Traffic-counting definitions, underlying AIS trajectory records, spatial fairway polygons, chart identifiers and editions, vessel-selection records, and measured obstacle inventories are not available within this secondary dataset. As a result, the analysis assesses internal arithmetic consistency rather than independent source-measurement accuracy.

3.4 Calculation of Monthly Vessel-Transit Intensity

To avoid mixing cumulative counts with monthly measures, the average monthly vessel movement $\bar{N}$ is obtained from the August and September counts. Fairway areas are converted to square nautical miles using $\mathbf{1\,nm = 1.852\,km}$. Mean monthly transit intensity T is then defined as:

$$T = \frac{\bar{N}}{A_{\mathrm{nm}^2}}; \qquad \bar{N} = \frac{N_{\mathrm{Aug}} + N_{\mathrm{Sep}}}{2}; \qquad A_{\mathrm{nm}^2} = \frac{A_{\mathrm{km}^2}}{3.429904} \tag{1}$$

Here, $\bar{N}$ is the two-month mean number of transits per month, A is fairway area, and T has units of transits per $\mathbf{nm^2}$ per month. This quantity indicates cumulative movement through a defined area during an average month; it is not a simultaneous number of vessels per square nautical mile.

3.5 Fairway-Geometry Screening Indices

3.5.1 Obstacle-Contact Geometry Index

An illustrative obstacle-contact index, I_G, describes the proportion of fairway width occupied by a selected vessel beam and an assumed effective obstacle width:

$$I_G = \frac{B + d}{W} \tag{2}$$

B denotes reference-vessel beam (m), d an effective obstacle width (m), and W navigable fairway width (m). Where several distinct obstacle widths are considered, the expression may be generalised illustratively as:

$$I_G = \frac{B + \sum d_k}{W} \tag{3}$$

For the three numerical examples, $\mathbf{d = 5\,m}$ is the value inferred algebraically from the tabulated percentages using $d = WI_G - B$. This reconstruction does not demonstrate that obstacles of that width were surveyed in all fairways. Individual obstacle measurements were not available, so Equation (3) was not separately applied. The percentage expression $\mathbf{100}I_G$ is used only for geometric screening and is not an observed grounding rate.

3.5.2 Fairway Length–Width Screening Index

A second dimensionless expression, I_S, characterises fairway elongation as a function of width W and length L:

$$I_S = 1 - \frac{2W}{\pi L} \tag{4}$$

W and L are expressed in the same units. For the cases considered, greater fairway length relative to width produces values closer to one. In the absence of a defined random-event model and empirical calibration, these numerical outputs cannot be interpreted as the probability that a ship will strand during a passage.

3.6 Analysis and Interpretation

The outputs were compared descriptively across the three cases. Transit counts and dimensioned fairway measurements were kept separate from the two screening indices. The indices were not combined into an overall risk score, as no empirical relationship, weighting system, or validation dataset was available to justify such aggregation. All percentage classifications are interpreted as relative geometric values and do not establish operational accident-risk thresholds.

4. Results

4.1 Fairway Characteristics

Table 1 presents the selected fairway geometry. Penang Port has the longest (13.4 km) and narrowest (0.2 km) of the three fairway configurations, while Port Klang has the widest fairway (0.5 km). The rectangular area values correspond to reported length × width products; actual navigable corridor boundaries could differ from this simplification.

Table 1. Selected fairway dimensions

Port	Length (km)	Width (km)	Area (km^2)
Port Klang	4.4	0.5	2.20
PTP	5.4	0.4	2.16
Penang Port	13.4	0.2	2.68

4.2 Vessel-Transit Volumes

The available monthly aggregates are shown in Table 2. Port Klang recorded 1,811 movements over the two-month interval, followed by PTP (743) and Penang Port (429). August and September totals are similar at Port Klang and PTP, whereas Penang Port shows a small decline in September.

Table 2. Vessel-transit totals, August–September 2025

Port	August 2025	September 2025	Two-month total
Port Klang	905	906	1,811
PTP	371	372	743
Penang Port	221	208	429

4.3 Area-Normalised Mean Monthly Vessel-Transit Intensity

Using Equation (1), mean monthly transit intensity is $\frac{1{,}411.72\ \text{transits}}{\text{nm}^2\ \text{month}}$ for Port Klang, 589.91 for PTP, and 274.52 for Penang Port (Table 3). For example, Port Klang has an area of $\frac{2.20}{3.429904} = 0.64142\,\text{nm}^2$ and a mean monthly count of $\frac{(905+906)}{2} = 905.5\,\text{transits}$. Its calculated intensity is therefore $\frac{905.5}{\left(\frac{2.20}{3.429904}\right)} = \frac{1{,}411.72\ \text{transits}}{\text{nm}^2\ \text{month}}$. The remaining values follow the same method, retaining the same month and area definitions for all cases.

Table 3. Mean monthly vessel-transit intensity

Port	Fairway area (nm^2)	Mean monthly transits	Intensity $(\text{transits}/\mathrm{nm}^2/\text{month})$
Port Klang	0.64142	905.5	1,411.72
PTP	0.62976	371.5	589.91
Penang Port	0.78136	214.5	274.52

4.4 Reference-Vessel Dimensions

Table 4 lists one reference vessel for each case. The selected vessels differ substantially in dimensions. Their beam-to-fairway-width ratios are 3.16% at Port Klang, 9.50% at PTP, and 22.00% at Penang Port. The reference vessels are illustrative selected cases rather than a verified sample of the largest vessels to transit each location.

Table 4. Reference-vessel particulars

Port	Reference vessel	LOA (m)	Beam (m)
Port Klang	DEVON EXPRESS	116.6	15.8
PTP	YAMATO	162.0	38.0
Penang Port	GENTING DREAM	335.0	44.0

4.5 Obstacle-Contact Geometry

Substituting the vessel beams, fairway widths, and inferred $d = 5\,\mathrm{m}$ into Equation (2) gives $I_G = 0.0416$ for Port Klang, 0.1075 for PTP, and 0.2450 for Penang Port, corresponding to 4.16%, 10.75%, and 24.50%, respectively (Table 5). The ranking is driven by both the selected beam and fairway width; it should not be interpreted as the relative frequency of grounding incidents.

Table 5. Obstacle-contact geometry index

Port	Reference beam (m)	Fairway width (m)	$I_G \times 100$ (%)
Port Klang	15.8	500	4.16
PTP	38.0	400	10.75
Penang Port	44.0	200	24.50

4.6 Fairway Length–Width Geometry

Equation (4) yields I_S values of approximately 92.77% at Port Klang, 95.28% at PTP, and 99.05% at Penang Port. For Port Klang, $1 - \frac{(2\times0.5)}{(\pi\times4.4)} = 0.92766$. The result approaches one as the selected fairway becomes longer and narrower. These are not empirical probabilities of stranding; the measure is a geometrical transformation of the length-to-width ratio.

Table 6. Fairway length–width screening index

Port	Length (km)	Width (km)	$I_S \times 100$ (%)
Port Klang	4.4	0.5	92.77
PTP	5.4	0.4	95.28
Penang Port	13.4	0.2	99.05

4.7 Cross-Port Comparison

The consolidated indicators in Table 7 highlight two distinct dimensions of the study. Port Klang has the greatest area-normalised vessel movement intensity but the lowest obstacle-contact screening ratio, whereas Penang Port has the lowest movement intensity and the greatest values of both geometry indices. Neither pattern demonstrates an observed ranking of accident frequency across the ports.

Table 7. Comparison of vessel-transit exposure and geometry screening

Port	Two-month transits	*Intensity*[1]	I_G (%)	I_S (%)
Port Klang	1,811	1,411.72	4.16	92.77
PTP	743	589.91	10.75	95.28
Penang Port	429	274.52	24.50	99.05

Note. [1]Intensity denotes mean monthly transits per nm^2 per month. I_G and I_S are dimensionless geometry indices shown as percentages; neither is a calibrated accident probability.

5. Discussion

5.1 Traffic Exposure and Navigational Geometry

The findings reveal a substantial contrast between movement exposure and geometric restriction. Port Klang's mean monthly transit intensity is about 5.14 times that of Penang Port, whereas Penang Port's obstacle-contact index is approximately 5.89 times the Port Klang value. These ratios describe distinct characteristics and cannot be directly compared as if they measured the same form of risk. Previous marine traffic studies similarly show that vessel movement statistics are useful for characterising activity but need additional modelling before they can support conclusions about hazards or incidents (Mustaffa et al., 2016; Ramin et al., 2020; Tu et al., 2018).

The selected reference-vessel dimensions contribute to the observed contrasts. Port Klang's 15.8 m-beam reference vessel occupies a smaller fraction of the assumed fairway width than the 44.0 m-beam vessel considered at Penang Port. Different sampling of the actual operating fleet could materially affect these comparisons. A refined study should apply vessel-size classes or full AIS traffic distributions instead of treating one selected ship as representative of an entire port.

5.2 Interpretation of Simplified Risk Expressions

The obstacle-contact and fairway-length/width expressions are fully reproducible from the stated inputs but are not calibrated to observed groundings or strandings. The inferred 5 m obstacle width must be distinguished from a measured hazard dimension. Similarly, the high values of the length–width index arise mathematically for relatively long fairways and therefore cannot be interpreted as a high percentage likelihood of stranding. The literature on quantitative marine risk consistently separates encounter or exposure modelling from the estimation of actual accident occurrence and associated consequences (Chai et al., 2017; Chen et al., 2019; Montewka et al., 2010).

Risk assessments intended for navigational decisions should incorporate more representative vessel particulars, chart-based channel geometries, accident observations, and relevant operating conditions. Bellsolà Olba et al. (2020) demonstrated the value of integrating several nautical-risk criteria into a port-oriented index. This broader approach is more suitable for comparing safety performance than assigning overall risk rankings on the basis of two uncalibrated geometric ratios.

5.3 Implications for Malaysian Port Risk Assessment

The three examples illustrate the importance of a common reporting basis for MTRA in Malaysia. Area definitions, measurement units, time windows, data-quality procedures, and vessel classifications should be transparent across port assessments. Before technological deficiencies are assigned to a particular port, available AIS reception, VTS coverage, operating procedures, and infrastructure should be verified against current port-authority records. The present numerical analysis does not establish comparative AIS or VTS capability.

5.4 Limitations

This comparison is limited to two monthly aggregates for each of three selected fairway cases. The available information does not establish traffic-count provenance, AIS completeness, precise fairway boundaries, hydrographic chart editions, individual obstacle dimensions, or the representativeness of the three reference vessels. Neither screening model was calibrated against incident histories, and environmental conditions, human performance, navigational aid availability, tug assistance, and ship-handling characteristics were not included. Accordingly, the results support an arithmetic and geometric comparison, but not causal conclusions or operational estimates of accident probability.

6. Recommendations for Maritime Safety Management

6.1 Adopt Consistent MTRA Reporting

Port-risk reporting should define fairway boundaries, collection periods, unique-vessel or transit counting rules, spatial units, and calculation methods. Standardised metadata and retained source records would facilitate replication and meaningful comparisons between ports (Bellsolà Olba et al., 2020; Tu et al., 2018).

6.2 Verify Monitoring Capabilities and Data Quality

AIS and VTS facilities should be assessed using current coverage maps, equipment inventories, operating procedures, and data-quality checks. Targeted improvements should follow documented operational needs rather than assumptions about a port's technological status.

6.3 Incorporate Validated Operational Risk Models

Future assessments should integrate directional flows, vessel sizes, route geometries, environmental factors, and encounter conditions, together with historical casualty data. Where probabilistic models are required, calibration and validation should be documented and predictive uncertainty reported (Chen et al., 2019; Montewka et al., 2010).

6.4 Extend Temporal and Spatial Coverage

Longer AIS observation periods and detailed spatial fairway polygons would permit study of traffic peaks, seasonal variation, route interactions, and changes in vessel composition. Sensitivity analyses should examine the effects of vessel beam, fairway width, effective obstacles, and boundary definitions on screening outcomes.

7. Conclusion

This study compared traffic exposure and fairway-geometry screening indicators for three Malaysian port-fairway cases. Based on August–September 2025 aggregates, Port Klang recorded the greatest two-month traffic volume (1,811 transits) and mean monthly transit intensity $\left(\frac{1{,}411.72\ \text{transits}}{\text{nm}^2}{\text{month}}\right)$, followed by PTP (743 and 589.91) and Penang Port (429 and 274.52). Under the selected vessel and geometric assumptions, the obstacle-contact indices were 4.16%, 10.75%, and 24.50%, while the fairway length–width indices were 92.77%, 95.28%, and 99.05%, respectively.

These differences demonstrate that vessel movement exposure and fairway geometry measure different aspects of navigational conditions. The geometric outputs are screening indicators rather than calibrated accident probabilities; accordingly, the findings cannot rank actual port casualty risk. Transparent spatial definitions, complete movement data, representative vessel sampling, and validation against operational incidents are essential for advancing reliable comparative MTRA and informing proportionate maritime safety interventions.

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Declaration of Generative AI and AI-Assisted Technologies

Generative AI-assisted technologies were used for language refinement, editorial organisation, and formatting. These tools were not used to generate research observations or replace the numerical inputs reported in this study.

Conflict of Interest

The author(s) declare that there is no conflict of interest regarding the research, authorship, and publication of this article.

Author Contributions

Data Availability Statement

The aggregate transit counts, fairway dimensions, selected vessel particulars, equations, and calculated indicators underlying the analysis are provided in Tables 1–7 and Equations (1)–(4). The availability of the underlying individual AIS records, chart-derived spatial files, and incident datasets has not been established.

Ethics Statement

The author(s) have complied with all applicable research ethics requirements throughout the conduct of this study.

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