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RESEARCH ARTICLE

# Coastal Traffic Safety Index Based on Marine Accident and Traffic Records

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## Abstract

**In this study, a comprehensive index for evaluating the degree of coastal traffic safety by simultaneously considering marine accident frequency, severity, and traffic volume was considered. To do so, the concept of Equivalent Property Damage Only (EPDO), which is widely used in the road transportation industry, was benchmarked to assess both frequency and severity of accidents. In addition, the total sailing distance of ships was chosen as a variable to explain traffic volume. Finally, a composite performance indicator called "M-EPDO per nautical mile" was built up, enabling the safety performance score for each type of ships in three criteria: on-board personnel safety, ship safety, and navigational safety, to be calculated. When the index was applied to 12 administratively-divided zones in Korea waters, the most vulnerable zone for safety and the type of ship with the lowest level of each criterion could be identified based on the index scores. Consequently, it is expected that this index will be an effective decision-making tool for selecting key targets to promote coastal traffic safety performance.**

*Keywords:* Coastal traffic, Coastal traffic safety index, Marine accident, Equivalent property damages only, Sailing distance

## 1. Introduction

Ships are a major means of engaging in a variety of economic activities, including primary production activities such as fishing, service industries such as tourism and leisure, as well as transportation for passengers and cargo. Consequently, marine accidents that occur on ships exhibit a greater variation in terms of types and the extent of damage, in comparison to accidents occurring on roads, railroads, and aviation, where transportation serves as the primary purpose. In the case of Korea waters, various forms of ship-related accidents have occurred over the past five years (2017–2021), totaling 14,100, including 1275 collisions, 425 groundings, 251 sinkings, 762 strandings, 927 safety negligence accidents, and 624 fire explosions [1]. In particular, more than 90% of these accidents occurred in coastal waters within the territorial sea. Coastal waters are often characterized by narrow waterways, the inflow of marine wastes that can entangle ship propellers, the establishment of offshore wind farms, fishing activities, and other factors that impede the smooth navigation of ships [2]. These obstacles contribute to the increased risk of marine accidents in coastal waters. Furthermore, unlike land transportation, where one-way traffic flow is formed due to the limited movement path of transportation by road or railroad, ships move freely in an open space called the sea, forming various traffic flows. As a result, the risk of accidents varies by coastal waters and type of ships [3–5]. As the sea is an open and vast space with constantly changing marine environments, the more systematic and efficient the government executes its maritime safety policies, the more effective the safety measures can be [6–8]. Deploying equal manpower and budget for safety measures in all coastal waters is

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inefficient and difficult to expect visible reduction in marine accidents. The policy resources that the government can allocate to secure coastal traffic safety are limited. Therefore, there is a need to establish an efficient safety management system that focuses on the high-risk coastal waters as a priority, implementing customized safety policies to improve safety. To achieve this, it is necessary to establish quantitative criteria to identify where high-risk coastal waters and what types of vessels are vulnerable to safety.

Generally, when assessing the degree of maritime safety, an absolute scale based on statistics, such as accident frequency and the number of fatalities resulting from accidents, is primarily considered [9]. The frequency of accidents and the number of fatalities can be instrumental in identifying accident-prone areas. However, it is difficult to determine which waters are relatively more dangerous between accident-prone sea areas when projecting multiple information such as the number of accidents, the extent of accident damage, the volume of ship traffic, and the types of ships passing through the waters. What is needed is an index, a single value that aggregates multiple key metrics and allows for relative comparison of safety levels. An index is a standardized value that is converted to a comparable value at an area or a point in time for cross-regional or time-series comparisons [10,11]. Indices are easier to understand and interpret than multiple performance indicators provided individually, and they are useful in facilitating policy promotion and benchmarking of national performance [12]. As such, stakeholders and practitioners may consider utilizing the index as a quick, seamless decision support tool for policy consumption [13].

Based on the above background, this study aims to construct a coastal traffic safety index that can quantitatively indicate the comprehensive safety performance level of coastal waters. The designed index is based not only on the traffic volume in the water area to be evaluated but also on the frequency and severity of marine accidents that occurred in the water area, categorized by type. Specifically, as a variable describing traffic volume, we considered the total distance traveled by each type of vessel that had a history of transiting the waters we wanted to evaluate. Sailing distance can indicate the density of traffic in a body of water, and as sailing distance increases, the frequency of exposure to navigation hazards increases. In general, as the sailing distance increases, fatigue can increase. Sailing long distances can be physically and mentally demanding, requiring continuous focus and endurance, in particular, fishing boats and leisure crafts [14]. Thus, sailing distance is suitable for relative risk comparisons between vessel types or coastal water zones. As a variable that explains the frequency and severity of marine accidents, we benchmarked “Equivalent Property Damage Only (EPDO)," which is mainly used to evaluate the safety level of road traffic, and established a new EPDO for marine traffic safety domain. The EPDO is a performance indicator for traffic safety that considers both the severity and frequency of accidents. The EPDO concept offers a number of advantages over other traditional indicators of traffic safety, such as the number of fatalities or injury accidents [15]. The index proposed in this study can offer distinct safety scores for each ship type across three criteria: onboard personnel safety, ship safety, and navigational safety. This allows policymakers and stakeholders to intuitively comprehend the results and facilitates the dissemination of the impact of implementing coastal traffic safety policy measures.

The remainder of this paper is organized as follows. Related studies are reviewed in Section 2. In particular, it explores the differences between this study and preceding studies that have analyzed similar subjects such as assessment of marine traffic safety. Section 3 describes the study methodology. Section 4 presents the results of case study and discusses the utilization of the designed index. Finally, Section 5 summarizes and concludes the study.

## 2. Literature review

Many studies have been conducted to evaluate the level of maritime traffic safety. First, studies have been conducted to identify marine accident hotspots around the world or in specific regions based on GIS and marine accident statistics. Huang et al. [16] utilized a GIS framework to analyze marine accidents from a global perspective. The study presented the hot spots worldwide with high visualization of marine accidents by buffer analysis and clustering analysis. Zhang et al. [17] extracted the hot spot area of global marine accidents using k-means clustering with kernel density estimation (KDE). The study demonstrated that the distributions of marine accidents by time and ship type are diverse in different accident types. Wang et al. [18] proposed identifying techniques for hot spots of global crude oil tanker accidents using the Zero-Inflated Negative Binomial regression model (ZINB) and KDE. These studies have evaluated and mapped risk based on marine accidents using GIS technology. Yang et al. [19] proposed a framework for marine accident prediction using KDE and spatial clustering. As a result, the study predicted which grid area is an accident-prone area based on machine learning models such as Random Forest and AdaBoost algorithms. In addition, Rawson et al. [20] showed the spatial modeling of marine accident risk using the ensemble tree-based algorithms of XGBoost and Random Forest. The study used the marine accident data, predicted collision and grounding frequency by ship type per grid. The spatial risk maps give decision-makers actionable intelligence to mitigate risk in areas with the greatest needs.

On the other hand, studies have also been conducted to develop safety indexes or evaluate safety levels for ships, not marine space. Li et al. [21] used binary logistic regression method and designed a ship safety index to estimate the probability of a ship's accident by considering internal variables such as ship age, ship size, ship type, classification society type, and external variables such as navigation zone, ship flags, time, and season. Eliopoulou et al. [9] collected data on marine accidents reported worldwide from 2000 to 2012, evaluated the safety level of ships based on the frequency of accidents by ship type, and analyzed the changes in the time series. Lu and Tseng [22] designed key performance indicators for safety evaluation on passenger ships in Taiwan. For this purpose, an exploratory factor analysis was conducted based on the results of a survey of 361 passengers, businesses, academics, and government workers. As a result, six key indicators were derived: safety facilities, ship structure, ship documentation, safety guidelines, navigation and communication facilities, and crew competence. Zaman et al. [23], Gaonkar et al. [24] designed an index to evaluate marine traffic risk more quantitatively based on information/data (mainly about the dynamic factors) from Automatic Identification System (AIS). Nieh et al. [25] also conducted a navigational risk assessment of inbound vessels in Keelung harbor by statistically estimating the movement patterns of ships and assessing the navigational risk based on collision probabilities based on AIS information. Similarly, Yim and Lee [26] proposed a risk assessment framework to estimate the most potentially high-risk situations between vessels and bridge piers. In the paper, two variables used for risk assessment were the probability of deviation angle and the probability of stopping distance between the vessel and the pier. The risk value was then estimated by calculating the ratio against the maximum value of these two variables. Gaggero et al. [27] built the method for the assessment of both safety and comfort degree of specific routes for each dry cargo ship, passenger ship, and tanker. In the study, the route safety was assessed by a series of safety indexes, which considered the ship response on a particular sea-state that is evaluated by means of a potential code based on the strip theory. Other studies, such as Olindersson et al. [28] and Monewka et al. [29], have focused on providing real-time risk forecasting information to support decision-making by operators who are the intended audience for the index.

The previous studies above have designed meaningful evaluation models by assuming a variety of factors that can affect safety, depending on the object they want to observe. However, limitations were identified in using the evaluation models as a decision-making tool to prioritize the factors to establish policies upon for securing coastal traffic safety, which was the purpose of this study. First, if accident risk areas are identified based on accident frequency [9,16−18], the assessment cannot reflect national coastal transportation characteristics. Conversely, if too many variables are included in the assessment independently, such as accident frequency, traffic, weather, marine environmental factors including waves, and human-related factors [21,22], it is difficult to estimate the impact of a single indicator on safety performance. This is because environmental factors causing accidents and outcome factors, such as accident frequency, can be interrelated and compounded to have a significant impact on the score. Second, models that can provide real-time accident probability information [19−21,23−29] can support navigators' decision-making, but these models are limited when used as policy indicators that verify the effectiveness of mid- and long-term safety measure implementation because safety scores change frequently over short periods of time. Marine accidents do not occur frequently, so it is difficult to directly predict the occurrence of future accidents [30].

The literature review indicates that this study can complement the previous studies and contribute to the existing body of knowledge by making the following research distinctions. First, in contrast to other studies, the level of safety is assessed based on both objective marine accident statistics and big data that can be extracted directly from the AIS. Therefore, rather than predicting the uncertain probability of an accident, a result-oriented evaluation system is established based on accident statistics and ship traffic volume. This approach can provide a more holistic and nuanced understanding of coastal traffic safety in the mid- and long-term base. Second, as a method to calculate the coastal traffic safety index, we designed a composite performance indicator, EPDO per nautical mile, which allows for the comprehensive evaluation of each ship's sailing distance, marine accident frequency, and damage magnitude. While the EPDO weighting concept is actively used to assess the safety level of road traffic, the reference about its application in the maritime domain is relatively rare. By benchmarking the EPDO concept, this study proposes an easy-to-apply evaluation framework that can calculate the coastal traffic safety index using a single composite indicator, rather than constructing multiple indicators. This approach ensures the consistent application of the index regardless of the type of vessel and coastal waters to enhance its use in selecting priority targets for safety policies.

## 3. Methodology

Fig. 1 shows a flow chart to measure the coastal traffic safety index. It is necessary to design indicators for measuring the safety performance of each ship type that passed through the evaluated waters so that the degree of traffic safety can be relatively compared between coastal waters. This study designed a composite performance indicator to measure the risk level of ships based on the frequency and severity of marine accident by type against the environmental factor of traffic volume.

### 3.1. Preprocessing - categorization of marine accident types

In ships navigating in coastal waters, various types of accidents may occur due to the individual or complex effects of technical and human factors inside the ship and environmental factors outside the ship. In addition, due to these accidents, damage to ships or facilities on land and offshore occurs, and cases where ship crew die, are missing, or

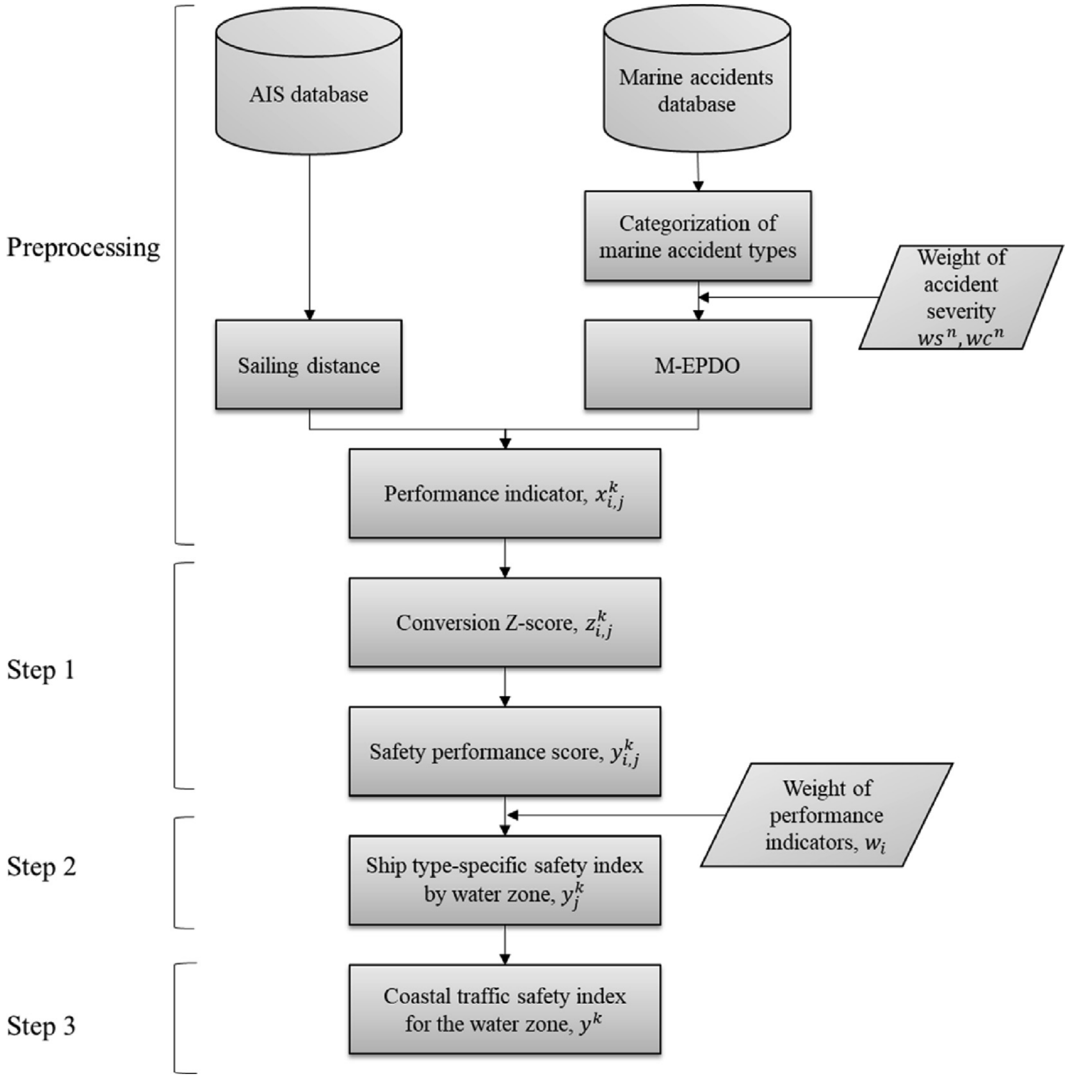

*Fig. 1. Flow chart to measure coastal traffic safety index.*

are injured occur. Therefore, marine accidents can be classified mainly according to the accident cause, accident type, and kinds of damage. However, it is impossible to estimate the cause of all accidents except for large-scale maritime disasters that require an investigation of the reason due to data limitations. Therefore, in this study, accident types are classified based on the categorization.

The International Maritime Organization (IMO) adopted the Casualty Investigation Code (CIC) through resolution MSC.255 (84) during the 2008 Maritime Safety Committee (MSC) session. According to the SOLAS regulation XI-1/6, each flag state is required to investigate marine casualties and incidents in compliance with the CIC. Particularly, under the CIC, very serious casualties that result in the total loss of a vessel, loss of life, or significant solid pollution must be reported to the IMO [31]. Generally, countries consider the harmonized reporting procedure established by the IMO when classifying casualty events. However, they may also customize accident classification to suit their national circumstances better and provide more detailed accident information. There are a total of 12 types of accidents classified in annual marine accident statistics [1] published by the National Maritime Safety Tribunal (NMST), a government agency of the Republic of Korea; overboard, engine trouble, propeller trouble, rudder trouble, fire/explosion, flooding, collision, contact, grounding, capsizing, sinking, winding with floating objects. However, the 12 types of accidents do not occur more than a certain level yearly on all types of ships. For example, the sinking or capsizing of a passenger ship is a very rare accident that does not occur every year, although the scale of human casualties is large. Therefore, it is necessary to reclassify by accident type. A group of 22 experts gathered and classified accident types depending on the direct cause of the accident or nature as shown in Table 1. In particular, due to the limited number of accidents in some marine accident types, these were grouped by similar accident causes. The main criteria for classifying marine accident types are − on-board personnel safety, ship safety, and navigational safety.

Category I of the marine accident is the accident from negligence of safety on-board such as man overboard, etc. Category II is a ship equipment damage incident such as engine, propeller, and rudder trouble. Category III is a poor ship maintenance, including fire, explosion, and flooding. Category IV is a nonoperational accident involving collision, contact, grounding, capsizing, and sinking. Finally, category V is the winding accident with floating objects. The performance classified into five types is assigned three kinds of criteria − on-board personnel safety, ship safety, and navigational safety.

### *3.2. Preprocessing − M-EPDO*

Both the frequency and severity of accidents are essential factors to consider. The EPDO weighting method for car crashes is commonly used as a standard of traffic safety analysis in American Association of State Highway and Transporation Officials (AASHTO) [32]. Using the EPDO method for hot spot identification is advantageous over others, such as frequency, because it incorporates accident severity data. EPDO crash count is the weighted sum of fatal, serious injury, minor injury, and no injury of an entity. All crashes have not occurred equally since fatal and severe injury crashes are far more costly to society than property damage-only (PDO) crashes. For example, according to Washington et al. [33], one minor injury crash is equivalent to 11 PDO crashes, one serious injury crash equals 949 PDO crashes, and one fatal injury crash is equivalent to 1330 PDO crashes, respectively.

However, the marine accidents have far greater social costs than automobiles regarding ship loss, cargo damage, and environmental pollution at sea. Thereby, applying to the maritime field the same weight values in the road traffic field is illogical. This study proposes Maritime Equivalent Property Damages Only (hereafter "M-EPDO"). To calculate the M-EPDO for each primary classified marine accident type, the severity of ship damage and casualties were categorized as shown in Table 2 [34].

Weights for each accident severity were set through a Delphi survey targeting a group of 22 experts who had participated in the categorization of marine accidents. As there is no clear standard for the weight, the experts' opinion was that the index should be used by adjusting it according to the national safety policy stance of the country to be used. Therefore, this study assigned weights according to the coastal traffic safety goal of Korea. The weight for the degree of ship damage and casualties were set equally as seen in Table 3. It is because the two goals of the Korea National Maritime Safety Basic Plan are a 30% reduction in marine accidents and human casualties, respectively [35].

M-EPDO can be presented as a single reference value by simultaneously reflecting accident frequency and severity type as following Equation (1).

*Table 1. Categorization of marine accident types.*

| Criteria | Marine accident category | Definition | Accident type |
|---|---|---|---|
| On-board personnel safety | Category I - Safety negligence accidents | The death, disappearance, or injury of a crew member, whether underway or at anchor, regardless of collision, capsize, sinking, etc. | Overboard and etc. |
| Ship safety | Category II - Ship equipment damage accidents | Damage to the propulsion system, main engines, auxiliary engines, fuel coolant pumps, steering, etc. that render the vessel inoperative. | Engine trouble<br>Propeller trouble<br>Rudder trouble |
| | Category III - Incidents of poor ship maintenance | A fire or explosion on board, resulting in property or personal injury, or water damage. | Fire/explosion<br>Flooding |
| Navigational safety | Category IV - Inoperability accidents | The vessel, whether underway or at anchor, strikes another vessel or facility, or the vessel capsizes, sinks, or runs aground on a sandbar, etc. and becomes unable to continue its voyage. | Collision<br>Contact<br>Grounding<br>Capsize<br>Sinking |
| | Category V - Operational obstruction accidents | The thrusters have wound up with a float and the ships are unable to continue sailing. | Winding with floating objects |

*Table 2. Classification of accident severity from marine accidents.*

| Classification | Accident severity | Description |
|---|---|---|
| Ship damage | Total loss | The vessel has sunk, become missing, or being otherwise unsalvageable where it is no longer possible to use as a ship, or the costs of repair are beyond economic feasibility owing to reasons such as running aground or on-board fire. |
| | Significant damage | The vessel is unable to operate under its own power, or it requires significant repairs to regain operability. |
| | Minor damage | Damage not categorized as total loss or significant damage. |
| Casualties | 1st class casualties | 2 or more fatalities. |
| | 2nd class casualties | 1 fatality, or 2 or more severely injured persons. |
| | 3rd class casualties | Injuries not categorized as 1st class or 2nd class casualties. |

$$M-EPDO=\sum_{n=1}^{N}(ws^{n}+wc^{n}) \tag{1}$$

where, $N$ indicates the number of marine accidents, $ws^{n}$ is weight by ship damage, and $wc^{n}$ is weight by casualty type of the $n$-th marine accident.

### 3.3. Preprocessing - performance indicator

Research on the analysis of fatality rates per billion kilometers traveled in road transport is active [36–38]. Moreover, Pay-As-You-Drive is applied according to the distance traveled. This means that as the mileage increases, the possibility of being exposed to the risk of a car accident increases, and the accident rate rises [39,40]. In this respect, the risk exposure frequency increases as the sailing distance of the ships increases. In addition, the sailing distance of ships has the advantage of considering all the degrees of marine traffic concentration in the coastal water zone. If the number of ships registered in two coastal water zones is the same, an equal comparison cannot be made because the area between the coastal water zones is different. Therefore, considering the sailing distance is suitable for comparing the relative risk between coastal water zones. The sailing distance was applied to the haversine, which is the straight-line distance between two points on a sphere, and the haversine calculation is as follows in Equation (2) [41]. The sailing distance can be calculated using AIS

*Table 3. Weight of accident severity.*

| Classification | Accident severity | Weight |
|---|---|---|
| Ship damage | Total loss | 5 |
| | Significant damage | 3 |
| | Minor damage | 1 |
| Casualties | 1st class casualties | 5 |
| | 2nd class casualties | 3 |
| | 3rd class casualties | 1 |

$$d_p = 2r\,arcsin\left(\sqrt{sin^2\left(\frac{\varphi_{p+1}-\varphi_p}{2}\right)+cos(\varphi_p)\cos(\varphi_{p+1})sin^2\left(\frac{\lambda_{p+1}-\lambda_p}{2}\right)}\right) \quad (2)$$

where, $\varphi_p$, $\lambda_p$ are the latitude and longitude of a ship by the $p$-th AIS record, respectively. $d_p$ is the distance between the $p$-th and $p$+1st positions.

The annual total sailing distance of ships in a specific coastal water zone is calculated by the following Equation (3).

$$d = \sum_{l=1}^{365}\sum_{m=1}^{M}\sum_{p=1}^{P} d_{m,p}^{l} \quad (3)$$

where, $M$ represents the number of ships navigated in the specific coastal water zone, and $P$ represents the number of track records of the $m$-th vessel collected per day. $d_{m,p}^{l}$ is distance between of the $p$-th and $p$ + 1st positions of $m$-th vessel at $l$-th day.

There is a large variance in the number of accidents per year by type of marine accident. Consequently, the range of change in the coastal traffic safety index is very high every year, making it difficult to grasp the trend of index change. It can be a factor that reduces the reliability of the index, especially when verifying the effectiveness of mid to long-term coastal traffic safety policies. Therefore, to address this problem, this study applied the moving average value of M-EPDO for the last three years. The performance indicator, $x_{i,j}^{k}$ for $i$-th marine accident category of $j$-th ship type in the $k$-th coastal water zone, is calculated as followings Equation (4).

$$x_{i,j}^{k} = \left(\frac{1}{3}\sum_{y-2}^{y} MEPDO_y\right) \Big/ d_j^k \quad (4)$$

where, $y$ represents the year to evaluate; in other words, the average M-EPDO up to the two years immediately preceding the year to be assessed are calculated. It is then divided by the sum of the total sailing distances $d_j^k$ of $j$-th ship type in the $k$-th coastal water zone.

This study classified observed ships into seven types: fishing boats (AIS ship type code 30), leisure crafts (37), cruise ships, passenger ships (40–49), cargo ships (70–79), tankers (80–89), and towing ships (31–32, 52). AIS ship type code of cruise ships is the same as the passenger ships. Accordingly, to distinguish cruise ships from passenger ships, the MMSI number of cruise ships was obtained from Korea Coast Guard, a safety management agency. Here, cargo ships include container ships, bulk carriers, and car carriers, while tankers include liquefied natural gas/liquefied petroleum gas carriers, very large crude carriers, and chemical tankers.

### 3.4. Step 1 - safety performance score

Step 1 converts the performance indicator to the safety performance score using Z-score and percentiles. The performance indicator is measured from Equation (4) and converted to a Z-score as followings Equation (5). In probability theory, the central limit theorem (CLT) establishes that, in many situations, for identically distributed independent samples, the standardized sample mean tends toward the standard normal distribution even if the original variables are not normally distributed. A minimum sample size of 30 is considered sufficiently large to see the effect and power of CLT [42].

$$z_{i,j}^{k} = \frac{x_{i,j}^{k} - \mu_{i,j}}{\sigma_{i,j}} \quad (5)$$

where, $\mu_{i,j}$ and $\sigma_{i,j}$ represent the mean and standard deviation of $i$-th marine accident category of $j$-th ship type for the performance indicator, $x_{i,j}^{k}$ in three years, respectively.

The Z-score value $z_{i,j}^{k}$ was converted into percentiles $y_{i,j}^{k}$ as following Equation (6) by fixing the same maximum and minimum values for each marine accident category. It was for comparing the performance indicator of the previous year and the current year and the vulnerability between the marine accident categories.

$$y_{i,j}^{k} = \frac{max_i - z_{i,j}^{k}}{max_i - min_i} \times 100 \quad (6)$$

where, $max_i$ and $min_i$ represent the maximum and minimum value of the $i$-th marine accident category, respectively.

### 3.5. Step 2 – ship type-specific index

In Step 2, the ship type-specific safety index is calculated by applying each global weight in Table 4

*Table 4. Weights of performance indicators by AHP.*

| Criteria | Sub-criteria | Local weight | Global weight |
|---|---|---|---|
| On-board personnel safety | Marine accident category I<br>- Safety negligence accidents | 1.00 | 0.46 |
| Ship safety | Marine accident category II<br>- Ship equipment damage accidents | 0.58 | 0.07 |
| | Marine accident category III<br>- Incidents of poor ship maintenance | 0.42 | 0.05 |
| Navigational safety | Marine accident category IV<br>- Inoperability accidents | 0.92 | 0.39 |
| | Marine accident category V<br>- Operational obstruction accidents | 0.08 | 0.03 |

to the five performance scores for the marine accident category obtained in Step 1 as following Equation (7).

$$y_j^k = \sum_{i=1}^{I} \left( y_{i,j}^k \times w_i \right) \tag{7}$$

where, $w_i$ is weight of the $i$-th marine accident category.

Analytic Hierarchy Process (AHP) was performed to set the weights for the marine accident category. The 9-point Likert scale valuation is used to measure the strength of the preference [43]. To familiarize respondents and their backgrounds, we asked preliminary questions about their affiliation and on-board experience. The survey was conducted with a total of 22 experts on maritime traffic safety, including academics, government-affiliated public institutions, PSC (Port state control) officer, VTS (Vessel Traffic Service) officer, Coast Guard, Maritime Affairs and Fisheries Division of local governments, and captains of shipping companies. Looking at the characteristics of the expert group who participated in the survey, two people (9.1%) had more than ten years of on-board experience, two people (9.1%) had 7–9 years, ten people (45.5%) had 4–6 years, and eight people (36.4%) had 1–3 years. Derivation of priorities in AHP requires calculating the consistency ratio (CR). The CR was used to determine the inconsistency in the pair-wise comparison made by the respondents. If the CR value is lower than the acceptable value of 0.2, the weight results are valid and consistent [43]. In contrast, if the CR value is larger than the acceptable value, the results are inconsistent and exempted from the analysis. By evaluating the CR of the collected questionnaires, 22 questionnaires appeared to have acceptable consistency. Table 4 shows that category Iof marine accident has a relatively higher weight than the other categories of marine accident that cause property damage, reflecting the importance of personnel safety.

### 3.6. Step 3 — coastal traffic safety index

Step 3 calculates the coastal traffic safety index by an arithmetic mean of the ship type-specific safety index obtained in Step 2 for each coastal water zone unit as following Equation (8).

$$y^k = \frac{1}{J} \sum_{j=1}^{J} y_j^k \tag{8}$$

Fig. 2 shows the concept of three steps to measure the coastal traffic safety index from Section 3.4 to Section 3.6 described above.

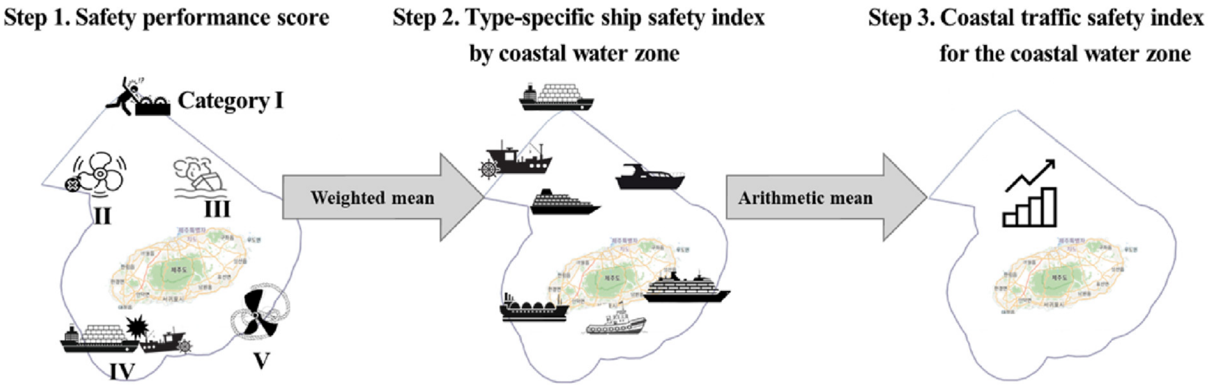

*Fig. 2. Concept for measuring coastal traffic safety index.*

## 4. Case Study

### 4.1. Study area and data description

According to the Korean Maritime Safety Tribunal (KMST) statistics, as 12,708 cases (approximately 90.1%) out of 14,100 marine accidents in the last 5 years have occurred within the territorial sea, it is necessary to introduce an index targeting the coastal water zone where most marine accidents occur [1]. Territorial sea refers to a specific range of waters connected to the territory of a country. It refers to a part of the state territory within which the sovereignty of a coastal state extends. Each country has the right to set the breadth of the territorial sea within the range of not exceeding 12 nautical miles from the baseline determined by the 1982 United Nations Convention on the Law of the Sea (UNCLOS) [44].

Fig. 3 shows the Republic of Korea (ROK) territorial water limit and boundaries of coastal water zones divided by administrative purpose. The dotted blue line is the boundary of coastal water zone, and the solid orange line represents the territorial waters limit of the ROK. The coordinate of coastal water zone boundaries is from the OpenStreetMap platform [45]. The ROK territorial sea extends 12 nautical miles from the outermost islands in the West and the South seas, which have many islands. Since Jeollanam-do has larger coastal water zone than those of others, it is necessary to subdivide them further. Jeollanam-do has two regional maritime affairs and port administration offices in Mokpo-city in the western region “E,” and Yeosu-city in the eastern region “F"; the coastal water zone of Jeollanam-do is classified into two regions based on their jurisdiction. Thus, 12 coastal water zones are targeted for this case study. The zone “A" and “J" include territorial waters of sub-islands, as shown in Fig. 3.

This study utilized three-year AIS data from 2019 to 2021. The data was obtained from the Ministry of Oceans and Fisheries of Korea. Furthermore, the present study used fishing boat location data. The Korea Coast Guard installed a wireless system for non-SOLAS fishing boats in the coastal waters. The system transmits the location of fishing boats, with a frequency of 897 MHz intervals of approximately 30s. The fishing boat location data, with three-year data from 2019 to 2021, was provided by Korea Coast Guard. In addition, marine accidents were obtained five-year from 2017 to 2021 from KMST [1].

### 4.2. Results and discussion

Fig. 4 shows the number of ships for the marine accident category IV in 2021 as a sample. A large number of accidents for category IV occurred in the zone “G.” Then, the coastal water zone “E,” “F,” and “L" occurred frequently in that order. Fishing boats have relatively more accidents than other ship types in many coastal water zones. Each accident was weighted according to severity type, namely ship loss and casualty, according to Table 3. Other categories I, II, III, and V followed the same procedure.

Table 5 shows the results of calculating the sailing distance for each type of ship operated in 12 coastal waters zones during 2021 as a sample. It can be seen that the sailing distance of fishing boats in each coastal water zone is relatively more than other ship types. This is because registered fishing boats are relatively more than other ship types. Following

| Abbreviation | Name of coastal water zone |
|---|---|
| A | Incheon |
| B | Gyeonggi-do |
| C | Chungcheongnam-do |
| D | Jeollabuk-do |
| E | Jeollanam-do;<br>western region |
| F | Jeollanam-do;<br>eastern region |
| G | Gyeongsangnam-do |
| H | Busan |
| I | Ulsan |
| J | Gyeongsangbuk-do |
| K | Gangwon-do |
| L | Jeju |

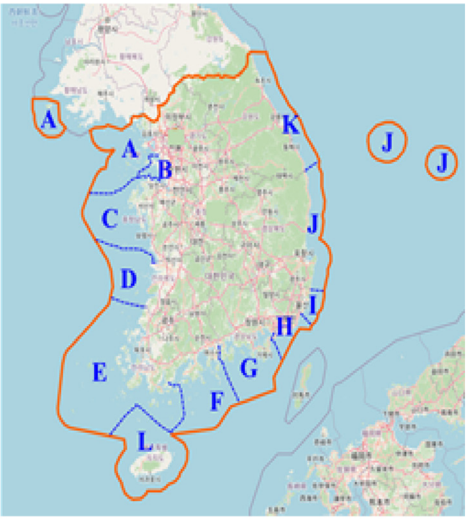

*Fig. 3. Twelve administratively-divided coastal water zones for case study and their abbreviations.*

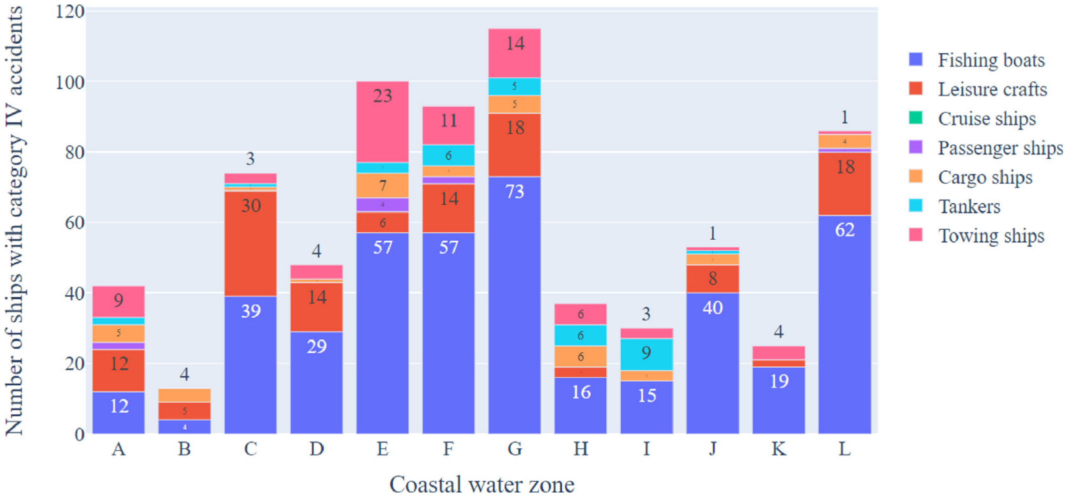

*Fig. 4. Number of ships with category IV accidents in 2021.*

fishing boats, cargo ships or tankers had relatively more sailing distance than other ship types.

Fig. 5 shows the box plot which contains outliers labeled "+" for the safety performance score, which is converted to 100 points after measuring performance indicators belonging to each marine accident category by ship type in 2021. The box plots provide overall patterns of safety performance scores for each marine accident category. The white circle in the box plots indicates the average of each item. In general, it was found that the average safety performance scores for fishing boats of each marine accident category are lower than other ship types. In particular, the safety performance score of cruise ships for the marine accident category I and III is not spread out due to the no accident during the year. Because the rate of sailing distance for cruise ships of each coastal water zones is relatively shorter than other types in Table 5, it was judged that those accident categories rarely occurred.

The maximum and minimum values for each marine accident category were set at 15.0 and −2.5, respectively, in Equation (6). These values are from the three times by minimum and maximum of z-scores. As a sample, Fig. 6 shows the safety performance score belonging to each marine accident category by ship type in the coastal water zone "H" in 2021. It turns out that cargo ships are relatively vulnerable in the marine accident category I and III in the coastal water zone, "H." Fishing boats are relatively vulnerable in the category and V.

Fig. 7 shows the safety performance score for each type of ship in three criteria: on-board personnel safety, ship safety, and navigational safety, at the coastal water zone, "H" in 2021 as a sample. The values are resulted from applying local weights in Table 4 to the consequence of Fig. 6. It is found that cargo ships are relatively vulnerable in the human and ship safety criteria at the "H" zone. In addition, fishing boats are relatively vulnerable in the navigation safety field.

*Table 5. Sailing distance of ships operated in 12 coastal water zones for case study during 2021.*

| Coastal water zone | Sailing distance (unit: nm) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Fishing boats | Leisure crafts | Cruise ships | Passenger ships | Cargo ships | Tankers | Towing ships |
| A | 4,595,899 (65.1%) | 390,010 (5.5%) | 177,317 (2.5%) | 525,700 (7.4%) | 796,608 (11.3%) | 292,873 (4.1%) | 280,574 (4.0%) |
| B | 814,236 (54.6%) | 57,500 (3.9%) | 42,334 (2.8%) | 64,355 (4.3%) | 296,021 (19.8%) | 137,772 (9.2%) | 80,160 (5.4%) |
| C | 7,736,647 (74.8%) | 308,146 (3.0%) | 4670 (0.05%) | 166,533 (1.6%) | 1,247,700 (12.1%) | 844,728 (8.2%) | 30,468 (0.3%) |
| D | 4,090,541 (77.5%) | 320,584 (6.1%) | 13,444 (0.3%) | 82,244 (1.6%) | 436,788 (8.3%) | 197,468 (3.7%) | 137,583 (2.6%) |
| E | 10,583,707 (53.5%) | 853,097 (4.3%) | 46,061 (0.2%) | 1,473,945 (7.5%) | 4,483,474 (22.7%) | 1,779,153 (9.0%) | 553,503 (2.8%) |
| F | 8,326,353 (61.8%) | 698,603 (5.2%) | 52,044 (0.4%) | 313,467 (2.3%) | 2,208,533 (16.4%) | 1,375,362 (10.2%) | 494,161 (3.7%) |
| G | 12,106,632 (66.9%) | 498,390 (2.8%) | 98,788 (0.5%) | 430,107 (2.4%) | 2,468,042 (13.6%) | 1,760,472 (9.7%) | 741,500 (4.1%) |
| H | 2,477,914 (44.0%) | 209,726 (3.7%) | 33,761 (0.6%) | 18,520 (0.3%) | 1,222,148 (21.7%) | 1,236,514 (22.0%) | 431,147 (7.7%) |
| I | 1,204,158 (37.3%) | 253,585 (7.9%) | 6999 (0.2%) | 23 (0.0%) | 520,625 (16.1%) | 859,271 (26.6%) | 379,859 (11.8%) |
| J | 2,721,985 (60.8%) | 184,233 (4.1%) | 543 (0.0%) | 29,882 (0.7%) | 1,115,660 (24.9%) | 253,768 (5.7%) | 172,489 (3.9%) |
| K | 1,883,989 (78.6%) | 78,424 (3.3%) | 407 (0.0%) | 14,817 (0.6%) | 232,340 (9.7%) | 50,607 (2.1%) | 136,231 (5.7%) |
| L | 5,588,242 (69.5%) | 387,370 (4.8%) | 61,765 (0.8%) | 223,912 (2.8%) | 1,241,153 (15.4%) | 494,956 (6.2%) | 43,499 (0.5%) |

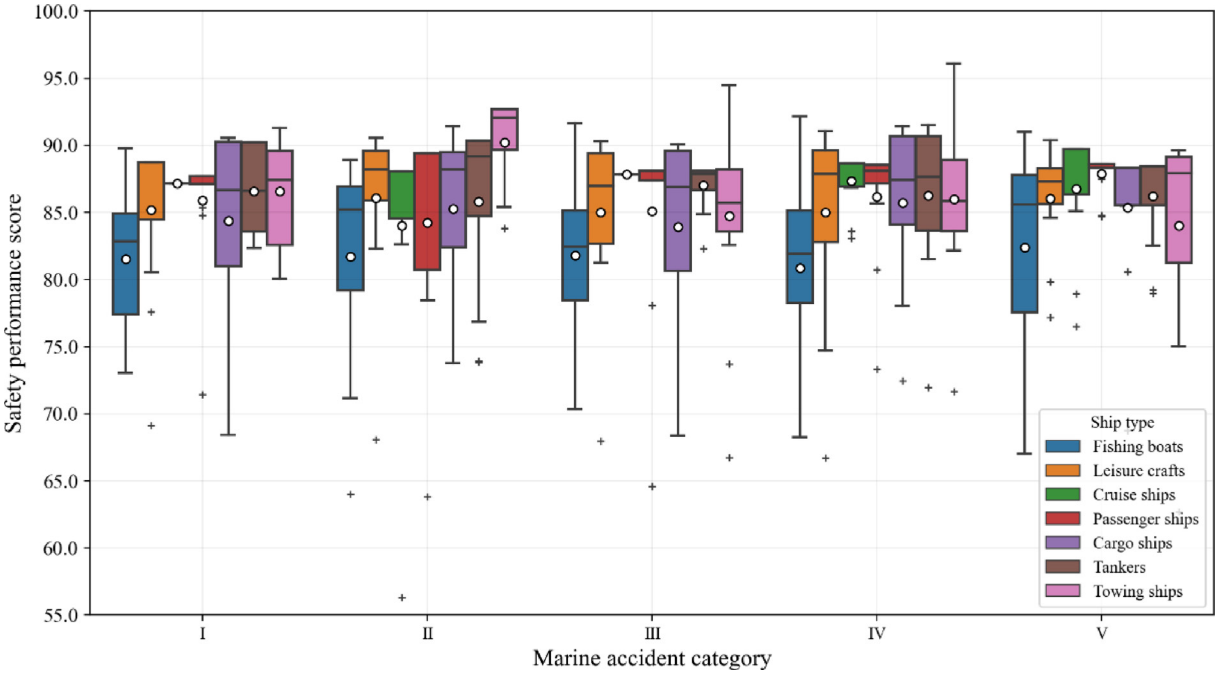

*Fig. 5. Box-plot for safety performance score in 2021.*

As a sample, Fig. 8 shows the ship type-specific safety index at the coastal water zone, “H” in three years. It can be seen that the index for cargo ship is relatively vulnerable compared to other ship types, and it tends to decrease every year in the coastal water zone, “H.” It is analyzed that the coastal water zone, “H” is due to frequent inbound and outbound cargo ships such as container ships because there are Busan Port and Busan New Port, the seventh largest container port worldwide in cargo throughput [46]. The ship type-specific safety index is easy to identify which ship type is relatively vulnerable in a specific area. The ship type-specific safety index is obtained from five safety performance scores. Therefore, if a 10-point difference in the ship type-specific safety index between the two coastal water zones means the difference of summation for the five safety performance scores is approximately 50 points.

Fig. 9 shows the coastal traffic safety index of 12 case study coastal water zones in three years. The coastal traffic safety index in the coastal water zone,

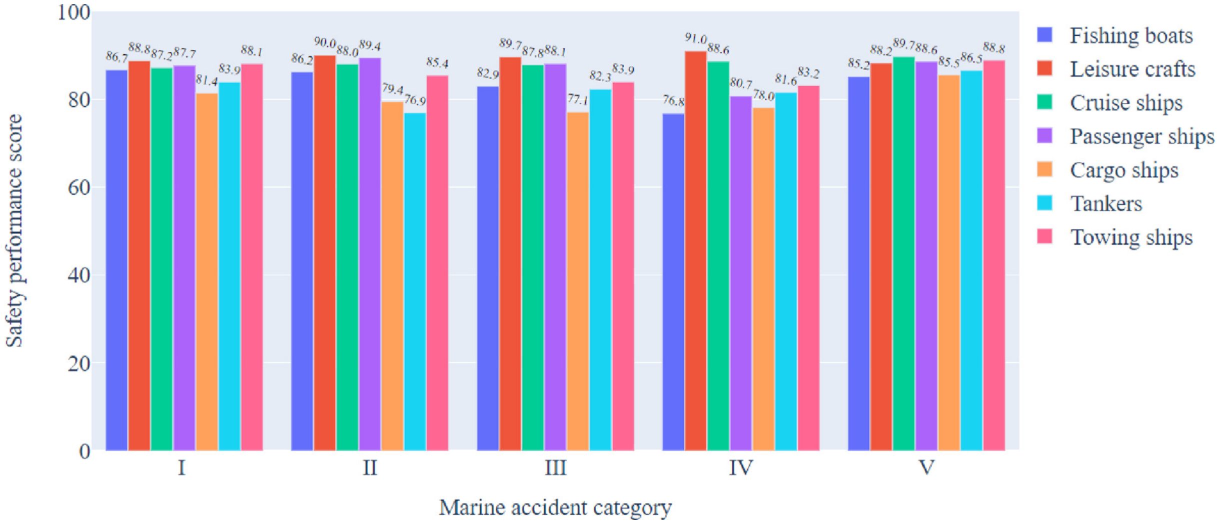

*Fig. 6. Safety performance score for marine accident category by ship type at the coastal water zone, “H” in 2021.*

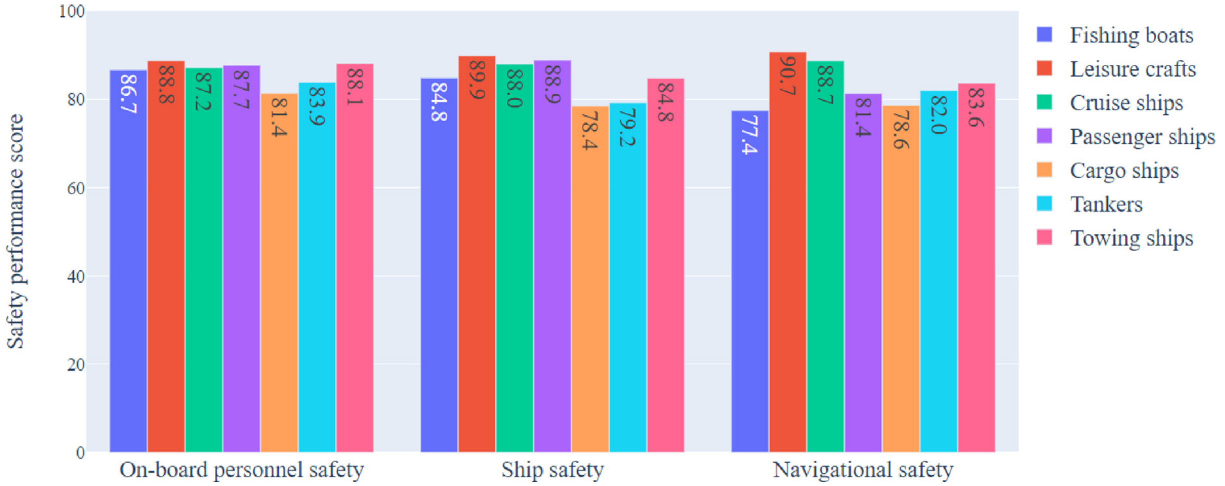

*Fig. 7. Safety performance scores for on-board personnel safety, ship safety, and navigational safety by ship type at the coastal water zone, "H" in 2021.*

"G" has been high for three years. The coastal traffic safety index in the coastal water zone, "C" has improved yearly, while that of the "H" and "J" tends to decrease yearly. This index makes it easy to identify the spatial extent to which areas are relatively vulnerable. It is judged that this index can be used as a valuable tool for making rapid decision-making by the government to establish measures to improve maritime traffic safety.

Even though the number of ships with category IV accidents occurred much more in the coastal water zone "G" than "H" in Fig. 5, the coastal traffic safety index in the zone "H" is lower than "G." The findings stem from intricate elements, including the weighted mean of the five performance indicators and the arithmetic mean of the seven ship types. Analyzing one of the complex factors, as shown in Fig. 4 and Table 5, the number of fishing boats with category IV accidents in the coastal water zone "G" is 4.5 times greater than in zone "H," and the sailing distance of fishing boats in zone "G" is 4.9 times greater than "H." This implies that the denominator of the performance indicator has relatively increased in zone "G." Therefore, the safety performance score for fishing boats in zone "G" may be slightly higher than "H." Consequently, it becomes apparent that the ship type-specific safety index and the coastal traffic safety index are not calculated as low merely due to a high number of accidents.

When considering the overall results of the case study, it becomes clear that the index designed in this research can inform which safety policy should be

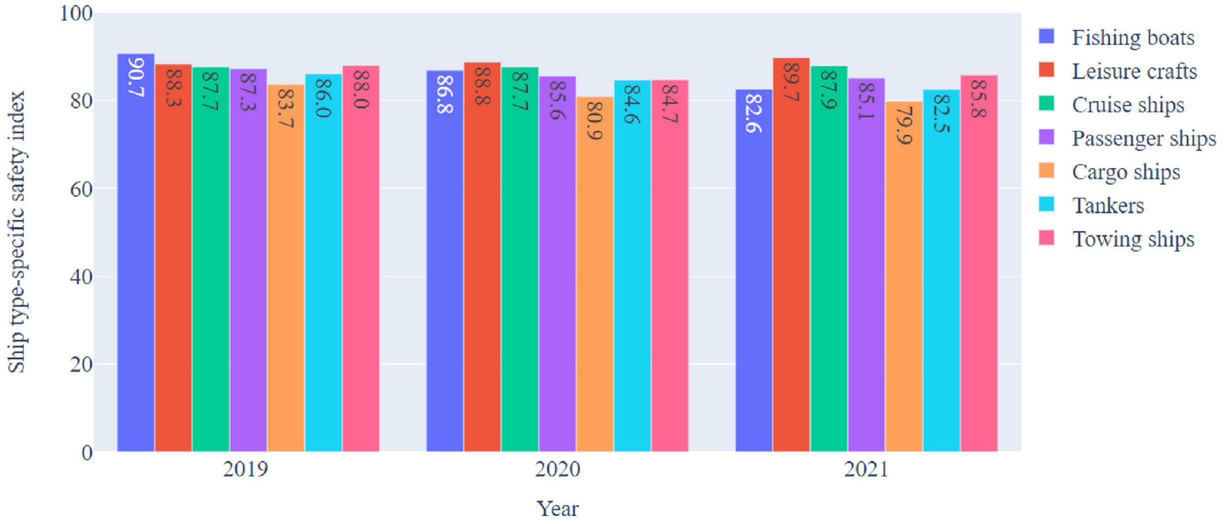

*Fig. 8. Ship type-specific safety index at the coastal water zone, "H."*

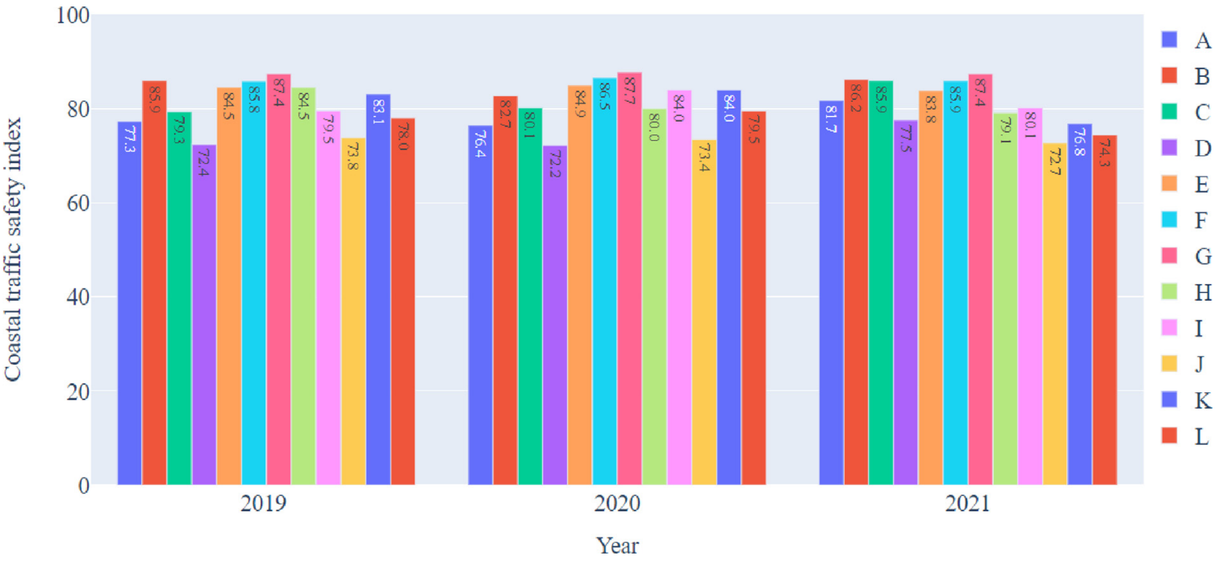

*Fig. 9. Coastal traffic safety index for 12 coastal water zones.*

strengthened or improved. Specifically, attention should be given to the coastal water zone, “H,” where the coastal traffic safety index has decreased for three consecutive years. As shown in Fig. 8, the ship safety index for cargo ships was found to be low in the “H” zone. Furthermore, Fig. 7 revealed that the safety performance score for cargo ships in the ship safety and navigational safety criteria was lower than that in the on-board personnel safety criterion. Fig. 6 also indicated that cargo ships were particularly vulnerable to marine accident category III. Therefore, it is recommended to strengthen the PSC when cargo ships enter the port as a customized safety management plan for this coastal water zone. The case study demonstrates that the designed index can effectively identify the most vulnerable coastal water zone in the study area. Using a top-down approach, decision-makers can determine which ship types have low safety performance and which marine accident categories require improvement, thus providing actionable intelligence to mitigate risks in coastal waters that require attention.

## 5. Conclusion

This study was conducted to develop a coastal traffic safety index model that can be used as a policy decision-making tool to quickly identify vulnerable waters that are priority targets for national coastal traffic management measures. The coastal traffic safety index designed in this study provides information on how many accidents occurred in ships with a history of operating in the evaluated waters and the accident severity caused by each of the five marine accident categories relative to the sailing distance. The index quantifies the safety level of ship type and waters being assessed on a scale 100. For the calculation of the coastal traffic safety index, a composite performance indicator called “M-EPDO per nautical mile” was built up, enabling the safety performance score for each type of ship in three criteria: on-board personnel safety, ship safety, and navigational safety, to be calculated. M-EPDO is a concept benchmarked from the road transportation field to assess both the frequency and severity of accidents.

In this study, the index was applied to 12 coastal waters in the territorial waters of the Republic of Korea, which were categorized for administrative purposes during 2019–2021. The sailing distance of each vessel was calculated using the haversine formula based on dynamic and static information obtained from positioning devices such as AIS. The results of case study showed that the variation in index scores between the 12 water bodies ranged from a maximum of 16.8% to a minimum of 1.7% per year on average. Thus, the index scores were effective in identifying the water bodies vulnerable to safety.

The coastal traffic safety index designed in this study addresses a limitation of existing methods, which separate the frequency of marine accidents from the number of casualties. Instead, it proposes a simplified approach using EPDOs, which are clear standardized values similar to those used in road traffic. This index makes it possible to identify the relative risk of different coastal water zones, even when the absolute frequency of accidents is the same. Consequently, the index system is expected to enhance policy efficiency by enabling differentiated policy support based on the level of risk. For instance, waters with index scores within the bottom 10th percentile or those experiencing a continuous decline in the index could be designated as special traffic safety diagnostic waters for policymaking. This would facilitate the implementation of targeted follow-up measures, such as analyzing accident risk factors and identifying improvement strategies. In the case study, our study highlighted the need to prioritize safety measures to reduce marine accident category III for cargo ships in a coastal water zone where the index had consistently declined over three years.

As a limitation of this study, it is judged that a more accurate index will be calculated if the weight according to severity of accident type is improved. In this study, the same method as in the road traffic field could not be applied due to a lack of data to convert total and partial ship loss into PDO. This will require further research.

## Conflict of interest

There is no conflict of interest.

## Acknowledgments

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