Development of Priority Index for Intelligent Vessel Traffic Monitoring System in Vessel Traffic Service Areas

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Abstract: Recognizing dangerous situations in advance and determining priority is essential in vessel traffic surveillance. The traffic management priority is determined by the vessel traffic service operator (VTSO) employing the closest point of approach (CPA) and the time to CPA (TCPA) of the targets considering their current navigational data. Various environmental conditions influence CPA and TCPA, which affects the importance of surveillance. This study aims to support vessel traffic prioritization in the navigation surveillance of VTSO from the observer side. The vessel tracks were clustered based on density, and a priority index of the vessel surveillance was developed in the VTS area by reflecting regional navigation characteristics. Density-based spatial clustering of applications with noise (DBSCAN) was used for data clustering to classify the surveillance area. A fuzzy membership function was constructed based on the CPA and TCPA belonging to each cluster, and a dataset for determining priorities was constructed, yielding 17 clusters, fuzzy rules, and tables, with the priority index extracted for all vessel pairs to visualize the priority. The results indicated prior recognition of all dangerous situations. The proposed method facilitates vessel surveillance priority determination in high-density areas and predicts the risk in advance, thereby contributing to traffic management.

Keywords: vessel traffic service; data clustering; collision risk detection; fuzzy theory; machine learning; surveillance prioritization; decision-making support

1. Introduction

In ports and adjacent waters, several vessels use a designated route to enter or depart a port and navigate the limited sea area, resulting in a high vessel density. It is known that the composition of the route connecting ports to ports can help predict the congestion level of the harbors and traffic volume based on the prediction of the demands of vessels’ calls [1,2]. This concentration of port logistics results in an increase in the density of ships, which can further cause potential marine accidents due to ship traffic in harbors. The maritime accident statistics of the Korean Maritime Safety Tribunal (KMST) indicate that during the years from 2016 to 2020, there were 13,687 cases of marine accidents in Korean territorial waters. During this period, 1713 cases occurred in ports and adjacent waters [3]. Consequently, several countries have adopted vessel traffic service (VTS) to prevent such potential marine accidents, and vessel traffic is efficiently and safely managed by a vessel traffic service operator (VTSO) through temporal and spatial coordination [4]. It is essential to the process of traffic management that the priority of vessel traffic be determined by recognizing the risk situations related to shipping traffic in advance, such as the surveillance of vessel movements, collisions, and stranding [5]. To monitor the movement of ships and prevent dangerous situations, such as collisions between ships, it is necessary to have the ability to predict future situations from the given information [6]. The VTSO should determine its own priority for efficient management of traffic and

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subsequently ensure compliance in the work process. In the process of prioritizing traffic management, the VTSO determines the priority based on the ships’ dynamic and static information, such as the closest point of approach (CPA) and the time to CPA (TCPA) to the target ships. However, the criteria for determining such priorities are formed in various ways, depending on the environmental factors of the area where the ship navigates. The current VTS operation process relies on subjective judgment of the VTSO to determine such priorities, and research related to this topic is insufficient. Since the current VTS system does not suggest priorities by reflecting the factors according to the navigation environment, it depends on the subjective decision making of the operator, which inevitably increases the task load of the operator. The mutual risk between ships is primarily focused on assessing the risk of collision. This idea is also used in the VTS system to determine any collision risk and to produce ship-oriented information to deliver the information to the ship. Research on collision risk includes the determination of a ship’s safety domain and risk. The concept of the domain was proposed by Fujii and Tanaka (1971) [7], and a domain composed of various shapes and sizes was developed considering the encountering relationship based on the International Regulations for Preventing Collisions at Sea (COLREGs) and other navigational conditions [8,9]. Recently, various calculation methods for collision risk have been proposed, as real-time data can be collected using an automatic identification system (AIS). Further, methods for determining and predicting the risk level using fuzzy theory or other machine learning theories have also been proposed [10,11]. However, these related studies are efforts to predict the risk of collision based on the self-referent (‘own’) ship and utilize it as a navigation aid for ships.

This study proposed an index for determining the priority of vessel traffic monitoring based on observers. Collision risk has been defined in previous studies by considering the relative value of the risk that a ship may have based on itself. However, the diversity of the safety distance that is formed differently depending on the area the vessel navigates was not considered. The vessels navigate closer while maintaining a relatively small CPA in narrow waters and act with appropriate TCPA considering the situation reflecting both altering course and collision avoidance simultaneously, in a route that requires a change of course. Therefore, when determining the priority of vessel navigation surveillance, these regional characteristics should be reflected, and the differently formed CPA and TCPA should be considered regionally. Consequently, this study proposed a method for determining the overall priority of the entire monitoring area by clustering the ships’ location-based data and assigning a priority that reflects the navigational characteristics in each area. Density-based spatial clustering of applications with noise (DBSCAN) was used for data clustering, which is a representative density-based clustering method. Identification numbers were assigned to each region according to the clustering results, and a sub-dataset was constructed for data learning. Further, fuzzy rules and tables for prioritization were configured based on CPA and TCPA. The aim was to present a functional improvement method for the VTSO decision-making support system by extracting the priority index for all pairs of targets and visualizing the results.

The remainder of this paper is organized as follows. In Section 2, the characteristics of the VTS, the work process, and the main decision-making standards of the VTSO are described and presents the modeling and simulation processes. In Section 3, the simulation and research results are discussed. Finally, in Section 4, conclusions and future work are presented.

2. Materials and Methods

2.1. Review of VTS Operation

The VTS, which aids vessels to operate safely and efficiently at sea, started as the need for traffic management using onshore communication facilities and radar emerged because of the difficulties in properly operating port facilities with aids to navigation (AtoN) alone. The International Maritime Organization (IMO) adopted the guidelines at the 36th meeting of the Maritime Safety Committee in 1990, requiring governments of the parties to make
efforts to ensure that their vessels comply with or implement VTS regulations. Meanwhile, the International Convention for the Safety of Life at Sea (SOLAS) Chapter 5, Regulation 12 has stipulated the concept and purpose by stating, “VTS contributes to the safety of life at sea, the safety and efficiency of navigation, and protects the marine environment from harmful environments that maritime traffic may cause, thus contributing to the protection of adjacent shores, workplaces, and offshore facilities” [12]. As such, the IMO recognizes the value and importance of the VTS as a service that improves the safety and efficiency of vessel traffic and protects the environment. Moreover, when planning and installing a VTS, the parties are required to follow the “Guidelines for Vessel Traffic Services (IMO Resolution A.857 (20))” set by the IMO [13].

In addition to providing information for the safe operation of vessels, VTSs have become more actively involved in traffic management to improve port efficiency with an increase in traffic volume. However, to cope with navigational risks, the need for a VTS to obtain information on the planned entry route and navigation forecast information in advance has increased. The port management authority collects the vessel arrival and departure information and delivers it to the vessel to support the prediction of port traffic conditions. Consequently, the VTS is now in charge of both spatial and temporal coordination of vessel traffic, which is realized by controlling the arrival and departure times and vessel speed limits. The service provided by the VTS for vessel traffic coordination can be defined as the following services [13,14].

Information service (INS) aids vessel navigators in using information necessary for navigation-related decisions in a timely manner. It provides essential information to assist the on-board decision-making process; however, it does not directly participate in the process. This service provides information, including mandatory reporting of changes in procedures and movements within the VTS area, such as the location, intention, destination, reporting lines, working frequency or channel, weather or navigation information, and information on overall traffic conditions associated with the vessel.

Traffic organization service (TOS) aids in the prevention of dangerous traffic situations and maintain safe and efficient traffic. It can provide information to aid in the onboard decision-making process and supervise movements through advice, directives, and orders. It focuses on planning the traffic flow in advance, and is particularly useful when congested traffic conditions or the movement of a specific vessel interfere with the navigation of other vessels. This service establishes and operates procedures that prescribe priority for movement between vessels, allocation of routes, location reports, speed limits, and permits for passage.

The navigational assistance service (NAS) helps navigators make effective decisions in water or situations when encountering difficulties in navigation. It can be employed in addition to the INS or TOS and may provide navigation-related recommendations or instructions. This includes providing information such as the effective course and speed of the vessel; the relative positions of routes and waypoints; the degree of proximity to navigational hazards; the name, position, and intention of the vessel in transit; and, if necessary, issuing warnings.

Internally, the VTS is a human–machine system between the operator and the system, and the VTSO is primarily limited to the operations and maintenance of equipment related to the operation of the VTS. However, externally, mutual cooperation and communication are the primary tasks of a human-to-human system between the adjacent VTS and the target vessel. The work characteristics of the VTSO are defined as follows in the VTS task study using cognitive work analysis (CWA) [15].

- Simultaneous events: The situation changes every moment owing to the nature of shipbuilding, and the intention of the shipbuilder must be understood. Several ships may be simultaneously placed in the same situation, in different places, or under different circumstances.
- Time pressure: Decisions must be made within a limited time and prompt processing of work is required.
TCPA refers to the time required for two vessels to reach the CPA and the minimum distance between their vessel relationship pairs in the process of vessel traffic management. CPA and TCPA can be determined using the principle shown in Figure 1 [16–18].

\[ TCPA = \frac{D_{r}}{c_{o}} \frac{s(\theta_{r} - \alpha_{o} - \pi)}{V_{r}} \]  

where \( D_{r} \) denotes the relative distance between the own ship and the target ship, \( c_{o} \) the position (longitude, latitude), course, and speed of the target ship are expressed as \( x_{t}, y_{t} \), \( \theta_{t} \), and \( V_{t} \), respectively.

VTS, and the “Guidelines for Vessel Traffic Services (IMO Resolution A.857 (20))” specify the sea area where the VTS must be installed as follows [13]:

- High traffic density
- Traffic carrying hazardous cargoes
- Conflicting and complex navigation patterns
- Difficult hydrographical, hydrological, and meteorological elements
- Shifting shoals and other local hazards
- Environmental considerations
- Interference by vessel traffic with other marine-based activities
- A record of maritime casualties
- Existing or planned vessel traffic services in adjacent waters and the need for cooperation between neighboring states if appropriate
- Narrow channels, port configuration, bridges, and similar areas where vessel progress may be restricted
- Existing or foreseeable changes in traffic patterns resulting from port or offshore terminal development or offshore exploration and exploitation in the area.

VTS is significantly affected by geographical and environmental factors unique to the region, such as navigation density, marine accident records, port and route complexity, traffic interference, and hydrological, hydrological, and meteorological influences. These marine traffic environmental factors are the primary reasons for the establishment of the VTS, and the ”Guidelines for Vessel Traffic Services (IMO Resolution A.857 (20))” specify the sea area where the VTS must be installed as follows [13]:

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However, prioritization and decision making cannot be solely based on CPA; rather, it should be determined by referring to the TCPA, which is the time required to reach the CPA. A negative TCPA indicates that the CPA of both vessels has insufficient time to take collision avoidance measures. Therefore, CPAs and TCPAs are regarded as major factors that can predict the risk of sailing. However, the relationship between CPA and TCPA, which is used as a major factor in determining vessel traffic management priorities, can be interpreted as follows: the closer the CPA, the higher the priority; the closer the TCPA, the lower the priority.

Figure 1. CPA and TCPA.

If the position (longitude and latitude), course, and speed of the own ship are expressed as \( x_{o}, y_{o}, \theta_{o}, V_{o} \), the position (longitude, latitude), course, and speed of the target ship are...
expressed as $x_t, y_t, \theta_t, v_t$, then the CPA and TCPA of the two vessels are expressed as Equations (1)–(5).

$$D_r = \sqrt{(x_t - x_o)^2 + (y_t - y_o)^2}$$  \hspace{1cm} (1)

$$V_r = V_o \times \sqrt{1 + \left(\frac{v_t}{v_o}\right)^2 - 2 \times \frac{v_t}{v_o} \times \cos(\theta_o - \theta_t)}$$  \hspace{1cm} (2)

$$\theta_r = \cos^{-1}\left(\frac{V_o - V_t \times \cos(\theta_o - \theta_t)}{V_r}\right)$$  \hspace{1cm} (3)

$$CPA = D_r \times \sin(\theta_r - \alpha_t - \pi)$$  \hspace{1cm} (4)

$$TCPA = \frac{D_r \times \cos(\theta_r - \alpha_t - \pi)}{V_r}$$  \hspace{1cm} (5)

where $D_r$ denotes the relative distance between the own ship and the target ship, $V_r$ is the relative speed, $\theta_r$ is the relative course, $\alpha_t$ is the true bearing of the target ship, and $\alpha_r$ denotes the relative bearing.

The relationship between CPA and TCPA, which is used as a major factor in determining vessel traffic management priorities, can be interpreted as follows: the closer CPA is to zero, the closer the two vessels meet. A CPA of 0 indicates that the two ships will collide after a certain time. However, prioritization and decision making cannot be solely based on CPA; rather, it should be determined by referring to the TCPA, which is the time required to reach the CPA. A negative TCPA indicates that the CPA of both vessels has already been surpassed, whereas a TCPA close to zero indicates that the two vessels have insufficient time to take collision avoidance measures. Therefore, CPAs and TCPAs are regarded as major factors that can predict the risk of sailing. However, the allowable CPA and TCPA are formed in various ways depending on the area where the vessel sails. Therefore, in this study, CPA and TCPA were used as input data for major decision making, considering the clustering areas that can reflect navigation characteristics according to the navigation area.

2.2. Data Processing Sequence

The decision support system for vessel traffic surveillance and management follows the process illustrated in Figure 2 to obtain the priority pair for the vessel. The process includes pre-processing, location-based clustering, priority extraction using fuzzy logic, and overall final priority extraction for the entire target sea area to store the navigation information of the vessel through the AIS and configure the training dataset. First, ship navigation data are collected and stored using the AIS receiving equipment. In the pre-processing process, the received data are extracted according to the target area, where only the vessels in navigation are extracted, excluding any anchoring, mooring, or drifting vessels, based on the allowable speed range. Thereafter, data classification is performed according to the maritime mobile service identity (MMSI) number of the vessel, and position interpolation is performed according to the time interval by standardizing the location-data reception time of the vessel. Subsequently, the data after position interpolation according to the standard time are again classified and stored according to the MMSI number, and the adjusted time is assigned such that it can be called according to the reference time. The data classified according to the standard time constitute a sub-dataset formed on location-based clustering. However, as each sub-dataset reflects the environment according to the location, the proximity distance is different, and a cluster ID is assigned according to the clustering result, followed by the CPA and TCPA calculations. Consequently, a fuzzy membership function that reflects the navigational characteristics of a region can be extracted. Therefore, a fuzzy inference system (FIS) for each region can be configured and a VTS priority index (Pindex) can be obtained, which reflects each clustering characteristic, and the final overall priority can be obtained by comparing the obtained Pindex with the entire target sea area. Finally, this result is displayed on the electronic chart display and information system (ECDIS) to allow the VTSO to intuitively understand the situation, forming a prioritization system for VTS decision support.
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2.3. Data Pre-Processing

AIS provides automatic reporting between vessels and between vessels and land, and is used for vessel traffic analysis by providing navigation data of vessels. Further, it also contributes to navigation safety and facilitates vessel traffic management by autonomously and continuously exchanging information such as vessel identity, location, time, route, and speed [19]. The AIS receiver station on land stores all AIS data received in the VTS area as well as the entire AIS coverage of the vessel. In this study, the following data pre-processing is required because the experimental area is limited to the VTS area by specifying the target area. First, only the data for the target area were extracted from the entire dataset, and the data of vessels that did not move, such as anchoring, mooring, and drifting vessels, were removed. Next, the data were converted into position data according to the reference time by moving the position according to the received time, as shown in Figure 3. The AIS data set different reporting intervals, as shown in Table 1, according to the speed and status of the vessel, and transmit the information of the own ship in a manner such that the unit time is divided and the time slot is occupied, as shown in Figure 4 [19]. Simultaneously, it reserves another time slot for the next position message. The same procedure was repeated for all other AIS-equipped ships. Each minute of time for each designated frequency was divided into 2250 slots, yielding a total of 4500 slots for the two frequencies. In addition, each frame of 2250 slots was repeated every minute. Therefore, the navigation data, according to the time transmitted by the vessel, should be converted into a reference time unit and used as a reference for a specific unit time. Data classified according to unit time were stored as a dataset that had been pre-processed for data training and used in the next process.

Figure 2. Data processing sequence including data pre-processing, location-based clustering, priority extraction using fuzzy logic, and overall final priority extraction.
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Table 1. AIS station reporting intervals.

| Station Type                                      | Nominal Interval |
|--------------------------------------------------|------------------|
| AIS Class B speed < 2 knots                      | 3 min            |
| AIS Class A speed < 3 knots in ‘At anchor’ or ‘Moored’ status | 3 min            |
| AIS Class B speed > 2 knots                      | 30 s             |
| AIS Class A speed > 3 knots in ‘At anchor’ or ‘Moored’ status | 10 s             |
| AIS Class A speed 0–14 knots                    | 10 s             |
| AIS Class A speed 0–14 knots and changing course | 3 1/3 s          |
| AIS Class B speed 14–23 knots                   | 15 s             |
| AIS Class A speed 14–23 knots                   | 6 s              |
| AIS Class B speed > 23 knots                     | 5 s              |
| AIS Class A speed 14–23 knots and changing course, or speed > 23 knots | 2 s              |
| Search And Rescue Aircraft (airborne mobile equipment) | 10 s             |
| AIS Base Station                                 | 10 s             |
| AIS AtoN                                         | 3 min            |
| Transmissions of AIS Application Specific Messages | 3 min            |
| Transmissions of AIS Long-Range Reports          | 6 min            |

2.4. Data Clustering

The DBSCAN algorithm is a representative clustering methodology that is suitable for handling spatial data, including noise, based on the density of data in the same cluster. It functions in contrast to existing methodologies that divide the cluster using the distance between the data [20]. Research on clustering AIS data based on the DBSCAN algorithm is being actively conducted through the development of automatic navigation technology and the use of maritime data cloud services. A method aimed at clustering the AIS coordinate data to explore the latitude and longitude lattice and spot areas of the cluster range was recently proposed [21]. In addition, a model for analyzing ship route patterns and predicting dangerous situations using DBSCAN was introduced [22], and the ship trajectory anomaly detection models such as unexpected stop, deviation from the prescribed route, or inconsistent speed, were proposed [23]. The DBSCAN algorithm was also used in another case as a method to reconstruct the damaged or missing AIS coordinate data [24]. Recently,
to predict the spread of COVID-19, the AIS data and DBSCAN algorithm were used, and they helped predict infectious diseases in ports and neighboring countries [25]. The DBSCAN is widely used as a method for clustering data related to the AIS coordinates. To perform DBSCAN, data of various distributions can be clustered based on these parameters through the definition of minimum neighboring data (MinPts) and cluster size (Epsilon, Eps). Here, Eps is the radius for forming a cluster based on one piece of data, and MinPts is the minimum number of data points included in Eps to form one cluster. According to the parameter-based location information, each piece of data is classified into core, border, and noise points, as shown in Figure 5. If there are more data than MinPts in Eps based on any point in the dataset, point p is referred to as a core point. Meanwhile, a border point refers to a point that is not a core point but a piece of neighboring data of a core point. Further, noise points are data points that do not belong to a cluster; in other words, they are data excluding core and border points. The following definitions are required to apply the DBSCAN algorithm [20,26].

**Definition 1.** Eps-neighbourhood of a point: The Eps-neighbourhood of a point p is the set of points q in database D that lie within radius Eps of point p.

\[ N_{Eps}(p) = \{ q \in D | dist(p, q) \leq Eps \} \]
Definition 2. Directly density-reachable: If point $p$ is in the Eps-neighborhood of point $q$ and point $q$ is of high density ($|N_{Eps}(q)| \geq \text{MinPts}$), point $q$ is a core point.

\[
p \in N_{Eps}(q) \\
|N_{Eps}(q)| \geq \text{MinPts} \text{(core point condition)}
\]

Definition 3. Density-reachable: There exists a chain wherein $P_{i+1}$ from point $p$ to point $q$ is directly density-reachable from $P_i$.

Definition 4. Density-connected: If there is a point $o$ that is density-reachable with respect to points $p$ and $q$ in the same cluster, points $p$ and $q$ exhibit a density-connected relationship.

Definition 5. Cluster: A set of accessible points (density-reachable) with respect to core point $p$ is defined as cluster $C$, and all points in one cluster are points connected to each other (density-connected).

\[
\forall p, q : \text{if } p \in C \text{ and } q \text{ is density-reachable from } p \text{ wrt. Eps and MinPts}, \text{ then } q \in C \\
\forall p, q \in C : p \text{ is density-connected to } q \text{ wrt. Eps and MinPts}
\]

Definition 6. Noise: If $C_i$ is a cluster in Database $D$, this implies that a point does not belong to any cluster.

\[
\text{Noise} = \{ p \in D | \forall i : p \notin C_i \}
\]

2.5. Fuzzy Logic

When managing vessel traffic, the VTSO determines priority by determining the risk of the traffic situation. In general, this task is expressed as a collision risk analysis. However, for a VTSO that has to manage the efficiency and safety of the entire VTS area rather than the situations of individual vessels, the priority for vessel traffic management must be determined from a perspective different to the collision risk analysis of the vessel operator [27]. In other words, it should be possible to quantify and express a myriad of intermediate states, not simply the two perspectives of “dangerous” or “safe”, and consequently determine the ranking according to the degree. In a specific navigation area, vague perceptions such as “keep a very close distance” and “there is little time for collision avoidance” are determined by the subjective judgment of the VTSO. However, fuzzy logic can be used to quantify and express unclear values [28], as it provides a method to mathematically deal with the fuzziness of linguistic expressions. Fuzzy logic has been developed by many researchers since its introduction by Zadeh in 1965 [29]. Its use allows expressing the extent to which a certain element belongs to set $A$ from 0 (no membership) to 1 (full membership), rather than classifying it as to whether it belongs to set $A$ (true) or not (false).

Figure 6 shows a schematic of the FIS inference process. In fuzzification, the input data are received in the form of crisp data, and the extent to which they belong to each suitable fuzzy set is determined. In the rule evaluation, the fuzzy input is received and applied to the antecedent of the fuzzy rule to obtain a number representing the evaluation result of the antecedent, which is then applied to the membership function of the latter. Subsequently, the fuzzy set of all rules for the latter is merged into one. Further, in defuzzification, the integrated output fuzzy set is output as a single number through the Center of Gravity (COG).
Fuzzy logic begins with defining a membership function. In this study, fuzzy logic was used to calculate the existing collision risk index to define the membership function. Assuming that the prioritization index for ship traffic management can be expressed using two factors, CPA and TCPA, among the various parameters of the ship navigation data, the model is constructed. In the model by Özoga and Montewka, the risk levels of the two vessels were quantified, as shown in Table 2, and divided into four risk levels for each [10]. In addition, in studies that defined collision avoidance rules, collision avoidance action was applied between vessels according to the classification of the encountering relationship between ships, and the collision avoidance action was divided into four stages: collision, danger, threat, and attention [30,31].

Table 2. Definition of membership function.

| TCPA | Level 1 (No Action Required) | Level 2 (Action Initiation Time) | Level 3 (Final Action Initiation Time) | Level 4 (No Time to React) |
|------|------------------------------|---------------------------------|--------------------------------------|---------------------------|
| CPA  | Lack of collision hazard     | Lack of collision hazard        | Lack of collision hazard             | Lack of collision hazard  |
| level 1 | (No hazard)                 | Remote collision hazard         | Remote collision hazard              | Close collision hazard    |
| level 2 | (Minor hazard)              | Remote collision hazard         | Close collision hazard               | Very Close collision hazard|
| level 3 | (Real hazard)               | Close collision hazard          | Very Close collision hazard          | Collision imminent       |
| level 4 | (Collision)                 |                                 |                                      |                           |

Meanwhile, studies on ship auto-navigation using fuzzy expert systems calculated the collision risk according to two factors: CPA and TCPA [32,33]. Regarding the state variables used in the CPA and TCPA membership functions, PS, PMS, PM, PMB, and PB were selected for CPA, and NB, NM, NS, PS, PMS, PM, PMB, and PB were selected for TCPA, where S stands for small, M for medium, B for large, P for positive, and N for negative. The decision of the collision risk index (CRI) can be expressed as a two-dimensional matrix, and the CRI output by the inference rule exhibits a value between $-1.0$ and $1.0$. The closer the CRI is to $1.0$, the higher the risk of collision, and a negative sign corresponds to a case wherein the TCPA is negative.

Ahn constructed an initial fuzzy inference table by adopting the ideas of Hasekawa et al. and derived a modified membership function table using an adaptive network fuzzy inference system (ANFIS) based on the data collected through navigation simulation results [11,34]. In this study, an initial fuzzy inference table was constructed, as listed in Table 3, with reference to the results of previous studies.
Table 3. Initial fuzzy inference table of Pindex.

| APA   | CPA  | Danger | Threat | Caution | Attention |
|-------|------|--------|--------|---------|-----------|
| Danger| 1.0  | 0.9    | 0.7    | 0.4     |
| Threat| 0.9  | 0.8    | 0.6    | 0.3     |
| Caution| 0.7  | 0.5    | 0.3    | 0.2     |
| Attention| 0.5  | 0.3    | 0.2    | 0.1     |

In each cluster, D of CPA stands for danger, implying CPA is zero; T for threat, implying the minimum value; C for caution, implying the median value; A for attention, implying the maximum value. In addition, a variable value was applied according to the clustering area. Further, D of TCPA stands for danger, implying TCPA is zero; T for threat, implying 120 s; C for caution, implying 240 s; and A for attention, implying 360 s. Meanwhile, the TCPA decision criteria were applied via the conversion of the relative distance of the vessel into time according to the COLREGs rules and a guide to the collision avoidance rules of the IMO [30,35].

3. Results

The Mokpo Harbor is a trading port located in the southwest of the Republic of Korea and is the fourth harbor in South Korea. There are 35 berths, 14 anchorages, and a shipyard that can build Panamax-sized ships adjacent to the docking facilities in the harbor. The Mokpo Harbor has a sea route of approximately 30 nautical miles from the entrance of Gasa-do (the starting point of the Mokpo VTS area) to the north wharf, where the Mokpo Harbor VTS is located. There are islands, reefs, shallow water zones, and bridges in the entire route section, requiring caution for navigation because there are frequent bends requiring diagonal turns [36]. Further, regarding the waterways that lead from the western part of Mokpo, the flood and ebb currents flow northward and southward, respectively. The currents turn approximately 30 min after the high and low tide, and the current speed reaches 4.0~5.0 knots [36]. Therefore, the Mokpo harbor and VTS areas were selected as target sea areas because it is appropriate to perform there the simulation for extracting traffic priority.

The AIS data collected at the Mokpo Harbor VTS Center were used for the simulation, including all vessel navigation data for 30 days from 1 June to 30 June 2021. A total of 227,297,489 ship coordinates were collected during this period, and the extracted variables included the MMSI, date (including time), latitude, longitude, speed of ground (SOG), course of ground (COG), and heading data. In addition, the extraction ranges were 34°25′30″ N to 34°49′30″ N and 126°00′00″ E to 126°25′30″ E. The total data collection area is shown in Figure 7a, and the number of coordinates was reduced to 72,308,388 as a result of extracting data from the target areas of Figure 7b,c. After removing data on anchoring, mooring, or drifting vessels, 22,034,544 coordinates (930 vessels) were extracted. Further, Figure 8 shows a heat map prepared based on the density of 0 to 100 scales per pixel for the data following location-data refinement and location interpolation. Figure 8a shows the heat map created by classifying the received AIS data according to the target area, and Figure 8b shows the result created by extracting only the vessels navigating the target area, excluding vessels that are anchored, moored, or drifted. Figure 8c shows the results of position interpolation according to the standard time intervals. The data shown in Figure 8c were stored as data for clustering in the subsequent steps.
Figure 8b shows the result created by extracting only the vessels navigating the target area, excluding vessels that are anchored, moored, or drifted. Figure 8c shows the results of position interpolation according to the standard time intervals. The data shown in Figure 8c were stored as data for clustering in the subsequent steps.

Figure 7. Data extraction by target area: (a) data collected, (b) target area, and (c) data classified by target area.

Figure 8. Data pre-processing results by (a) target area, (b) target speed, and (c) position interpolation.

Next, the result of the position interpolation in Figure 8c was grouped by the same time zone. This is essential for extracting the priority for all vessels existing at the same time via the rearrangement of the various AIS data receiving times to standard times. In this process, datasets that underwent data pre-processing were sorted according to the time zone (a total of 2881) to build a database for simulation. In previous studies on CRI calculation conducted from the perspective of a ship shown in Figure 9a, the risk relationship was defined based on the data received at the current time considering the expecting traffic situations between the own ship and targets [10,11]; however, in this study, all traffic situations of existing ships in the target area were considered, as shown in Figure 9b. Therefore, the data for all ships that exist within the same reference time must be extracted.
relationship was defined based on the data received at the current time considering the expecting traffic situations between the own ship and targets [10,11]; however, in this study, all traffic situations of existing ships in the target area were considered, as shown in Figure 9b. Therefore, the data for all ships that exist within the same reference time must be extracted.

Figure 9. Comparison of risk perceptions of ship traffic situations in the identical conditions: (a) own ship’s point of view, and (b) VTSO’s point of view.

Figure 10 and Table A1 show the results of the DBSCAN simulation performed to select appropriate DBSCAN parameters. The selected cluster IDs are 17, and the calculated CPA and TCPA values from each cluster are used to set the fuzzy membership function. A fuzzy membership function was formed for each cluster ID, as shown in Table 4. In each cluster, D of CPA stands for danger, implying CPA is zero; T for threat, implying the minimum value; C for caution, implying the median value; and A for attention, implying the maximum value. A variable value was applied according to the clustering area. Further, D of TCPA stands for danger, implying TCPA zero; T for threat, implying 120 s; C for caution, implying 240 s; and A for attention, implying 360 s. Meanwhile, TCPA decision criteria were applied via the conversion of the relative distance of the vessel into time according to the COLREGs rules and a guide to the collision avoidance rules of the IMO.

Figure 11 shows the simulation results of Pindex extraction. The visualization result of the small map in Figure 11b was posted after extracting all priorities for the priority index results of all dangerous vessels. In the target area, the priority index results were found as follows: there was 1 case of near collision with priority index 0.85 or higher, 10 cases of high danger with index 0.8 or higher, and 93 cases of caution with index 0.7.

A verification simulation was performed with 18 VTSOs to verify whether the proposed VTS priority index can aid the VTSOs in decision making. The group was classified into two VTSO groups with nine operators each that searched for vessel pairs with and without the Pindex provided, respectively. Each group consisted of six operators with five years of experience and three operators with between five and ten years of experience. Subsequently, a method of checking the real-time navigation data of the target sea area, as shown in Figure 11a, and then searching for the vessel pair that requires priority control within the time limit, was applied. The total number of sailing vessels was 61, and the number of cases involving encountering vessels was 29. Thus, verification was performed by measuring the number and time of searches for a vessel pair under control within 30 s,
targeting 10 cases with a Pindex of 0.8 or higher. In the VTOS group using Pindex, all 10 cases were searched within 30 s, requiring 10.4 s on average. The successful search for a vessel pair within the time limit ensures timely maritime traffic management activities.

Figure 10. DBSCAN simulation results: (a) Eps 0.010/MinPts 5, (b) Eps 0.015/MinPts 5, (c) Eps 0.020/MinPts 5, (d) Eps 0.010/MinPts 10, (e) Eps 0.015/MinPts 10, and (f) Eps 0.020/MinPts 5.

Table 4. Range of CPA/TCPA by risk level.

| Risk Level | Cluster ID | CPA (Nautical Miles) | TCPA (Seconds) |
|------------|------------|----------------------|-----------------|
|            |            | Danger               | Threat          | Caution         | Attention        | Danger               | Threat          | Caution         | Attention        |
|            | #1         | 0.0                  | 0.1352          | 0.4376          | 0.7549          | 0                  | 120             | 240             | 360             |
|            | #2         | 0.0                  | 0.0712          | 0.7418          | 0.9997          | 0                  | 120             | 240             | 360             |
|            | #3         | 0.0                  | 0.3005          | 0.7040          | 0.9494          | 0                  | 120             | 240             | 360             |
|            | #4         | 0.0                  | 0.2677          | 0.7848          | 0.9996          | 0                  | 120             | 240             | 360             |
|            | #5         | 0.0                  | 0.2021          | 0.7354          | 0.9892          | 0                  | 120             | 240             | 360             |
|            | #6         | 0.0                  | 0.1936          | 0.6244          | 0.9618          | 0                  | 120             | 240             | 360             |
Table 4. Range of CPA/TCPA by risk level.

| Cluster ID | CPA (Nautical Miles) | TCPA (Seconds) |
|------------|----------------------|----------------|
|            | Danger               | Threat         | Caution       | Attention     | Danger | Threat | Caution | Attention |
| #1         | 0.0                  | 0.1352         | 0.4376        | 0.7549        |        |        |         |           |
| #2         | 0.0                  | 0.0712         | 0.7418        | 0.9997        |        |        |         |           |
| #3         | 0.0                  | 0.3005         | 0.7040        | 0.9494        |        |        |         |           |
| #4         | 0.0                  | 0.2677         | 0.7848        | 0.9996        |        |        |         |           |
| #5         | 0.0                  | 0.2021         | 0.7354        | 0.9892        |        |        |         |           |
| #6         | 0.0                  | 0.1936         | 0.6244        | 0.9618        |        |        |         |           |
| #7         | 0.0                  | 0.3336         | 0.6259        | 0.9182        |        |        |         |           |
| #8         | 0.0                  | 0.2225         | 0.6382        | 0.9822        |        |        |         |           |
| #9         | 0.0                  | 0.1938         | 0.6607        | 0.9861        |        | 120   | 240     | 360       |
| #10        | 0.0                  | 0.4122         | 0.6411        | 0.9445        |        |        |         |           |
| #11        | 0.0                  | 0.2886         | 0.4623        | 0.9004        |        |        |         |           |
| #12        | 0.0                  | 0.5340         | 0.7902        | 0.8500        |        |        |         |           |
| #13        | 0.0                  | 0.1323         | 0.5265        | 0.8603        |        |        |         |           |
| #14        | 0.0                  | 0.2100         | 0.4992        | 0.8359        |        |        |         |           |
| #15        | 0.0                  | 0.2704         | 0.8322        | 0.8679        |        |        |         |           |
| #16        | 0.0                  | 0.4503         | 0.6564        | 0.8625        |        |        |         |           |
| #17        | 0.0                  | 0.2546         | 0.6460        | 0.8664        |        |        |         |           |

Figure 11. Simulation results of Pindex extraction: (a) real-time navigation data of target area, and (b) calculated Pindex visualization results.

To verify the main results of the study, we compared the VTS operation on traffic management between the method used in the existing VTS system and the method of performing the task by presenting Pindex to the VTSO. The key strength of Pindex is that the priority of all ships in the entire target area can be considered simultaneously, rather than making a decision by listing the CPA and TCPA for each pair of ships. This implies that the VTSO responds to dangerous situations by recognizing the situations in advance according to their importance. In previous studies, collision risk was presented by classifying the levels of CPA and TCPA; however, the index was extracted using fixed CPA and TCPA level values without considering regional factors [33] or using a fixed ship safety domain [31]. In contrast, the algorithm in this study was constructed based on the...
fact that these main input values are not fixed, and are rather formed differently depending on the regional characteristics. The primary limitations of this study are that clustering was performed for a single reference time and region-based data clustering was performed without considering the type and size of the vessel. To be used for real-time VTS tasks, the predicted Pindex input parameters (CPA, TCPA, and cluster ID) should be used to provide regional and global Pindex prediction values for VTSO.

4. Conclusions

VTS systems and VTSOs are known for their contribution to the reduction in marine accidents. Nevertheless, detecting all traffic conditions in a timely manner during peak hours when vessels are densely populated is virtually impossible, even with additional operating methods, such as dual surveillance and central control surveillance for VTSOs. This study proposed the use of Pindex, the VTS traffic management priority index, to support decision making by extracting the priority of vessel traffic surveillance for VTSO. A simulation was performed using navigation data collected from the Mokpo Harbor and its adjacent waterways in South Korea. Consequently, the target sea area was clustered into 17 clustering IDs. After extracting the priority index from each ID, an integrated index was presented for the entire target sea area. By providing a quantified priority index that classifies CPA and TCPA into four levels of danger, threat, caution, and attention according to traffic conditions, VTSOs were visualized to recognize the situation in an intuitive manner. Ten high-risk group vessel pairs were extracted from the entire sea area and eighteen VTSOs were used to verify the effectiveness of the proposed Pindex. The VTSOs failed to search for an average of 4.1 ship pairs within the time limit without Pindex, whereas all vessel pairs were successfully searched with Pindex. In addition, the average search time of the VTSO group with the Pindex provided was 10.4 s, shortened from the average of 14.3 s for the VTSO group without the Pindex provided. Thus, through simulations for VTSOs to verify the effectiveness of the proposed Pindex, the VTSOs successfully searched all vessel pairs with the provided Pindex within time limitations. The results indicate that the proposed methods can overcome the problems identified in existing VTS systems: (i) surveillance failure due to situational awareness timeout by providing a data list of CPA and TCPA for all ship pairs, and (ii) the calculation of the risk index using fixed CPA and TCPA levels or ship safety domains without considering regional factors and characteristics. However, as the results of this study were obtained through an experiment by selecting a specific simulation area and period, its applicability to all sea areas and periods cannot be stated. In addition, the presented cluster chart has a limitation in that it is the result of a single slide. Furthermore, the data structure was not classified according to the size or type of the vessel, and the simulations were performed with all vessels that are required to participate in VTS regulation mandatorily. In future research, data analysis should be performed considering various factors, such as the segmentation of the dataset reflecting the type and size of the vessel and the environment with big data, to ensure that it can be applied to all sea areas. In addition, it is necessary to ensure the accuracy of the extracted priority index by reflecting the route prediction, including the coordinates with traffic patterns and the time required.

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Appendix A

Table A1. Cluster results by Epsilon and MinPts.

| ID     | Epsilon | MinPts | 0.010 | 10  | 0.015 | 10  | 0.020 | 10  |
|--------|---------|--------|-------|-----|-------|-----|-------|-----|
| Noise  |         |        | 120   | 277 | 47    | 189 | 30    | 110 |
| Cluster ID 1 |       |        | 10    | 213 | 10    | 10  | 18    | 17  |
| Cluster ID 2 | 236   | 12    | 291   | 249 | 461   | 298 |
| Cluster ID 3 | 9     | 18    | 7     | 29  | 17    | 61  |
| Cluster ID 4 | 27    | 11    | 59    | 56  | 15    | 41  |
| Cluster ID 5 | 9     | 10    | 30    | 14  | 14    |     |
| Cluster ID 6 | 5     | 14    | 16    | 12  | 10    | 14  |
| Cluster ID 7 | 46    | 12    | 6     | 17  | 11    |     |
| Cluster ID 8 | 12    | 9     | 25    | -   | -     | 10  |
| Cluster ID 9 | 7     | -     | 14    | -   | -     | -   |
| Cluster ID 10 | 5     | -     | 17    | -   | -     | -   |
| Cluster ID 11 | 11    | -     | 13    | -   | -     | -   |
| Cluster ID 12 | 5     | -     | 6     | -   | -     | -   |
| Cluster ID 13 | 7     | -     | 7     | -   | -     | -   |
| Cluster ID 14 | 5     | -     | 11    | -   | -     | -   |
| Cluster ID 15 | 9     | -     | 7     | -   | -     | -   |
| Cluster ID 16 | 5     | -     | 5     | -   | -     | -   |
| Cluster ID 17 | 6     | -     | 5     | -   | -     | -   |
| Cluster ID 18 | 6     | -     | -     | -   | -     | -   |
| Cluster ID 19 | 5     | -     | -     | -   | -     | -   |
| Cluster ID 20 | 5     | -     | -     | -   | -     | -   |
| Cluster ID 21 | 6     | -     | -     | -   | -     | -   |
| Cluster ID 22 | 15    | -     | -     | -   | -     | -   |
| Cluster ID 23 | 5     | -     | -     | -   | -     | -   |
| Total   |        |       | 576   | 576 | 576   | 576 | 576   | 576 |

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