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A New Risk Evaluation Model for Safety Management on an Entire Ship Route

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ABSTRACT: In this paper, we introduce a new risk evaluation model for evaluating the navigation safety zone for an entire ship route. This model considers a new algorithm to determine the navigational safety zone in real-time, and also takes the navigation officers' perception while navigating a ship into consideration. The risk quantification has been developed using a questionnaire and incorporated into the new model. A simulation was carried out for the Osaka bay area in order to verify the usefulness of the proposed model. A new approach was employed to monitor the level of navigation safety along a ship route. The entire ship route is divided into small sections as a gridded matrix. The level of navigation safety can be quantified by means of a safety index on the basis of the ship's navigation data within a specified distance range. The results show that the comparison between risks identified for different sections across the entire ship route is easy, which helps determine the navigational safety zone quickly. This model is expected to be able to serve as a new tool for managing safety throughout an entire ship route area in real-time in order to support the port safety authority or vessel traffic service center.

1 INTRODUCTION

A marine accident can have dire consequences such as the loss of ships, and damage to marine infrastructure and the environment. These accidents have led to economic losses and long recovery times. In order to prevent marine accidents, safety management is considered a significant issue in industrial shipping and ship navigation. It has come to light that there is a need to develop safety evaluation methods to enhance safety during ship navigation. Various navigational safety evaluation methods have, therefore, been proposed.

Fujii (1971) and Macduff (1974) proposed a ship collision probability model to determine a safe navigational zone. In these studies, the level of risk was calculated using statistical analysis of a marine accident and the traffic data. The obtained results indicated the potential risk of the collision or grounding of a ship. It can be helpful to distinguish the hazard zones in port area. However, the calculation result relies on historical data. When using this type of methodology, it is not possible to reflect real-time navigational situations.

Ship domain models have been proposed in research regarding safety evaluation models. A certain area around a ship, such as a circular, rectangular, elliptical, or polygonal shape, has been proposed. It is to remain clear of other ships. The shape and size of a ship's domain is determined by the calculated safe distance on the basis of statistical analysis of marine traffic data (Goodwin, 1975; Fujii, 1971), fuzzy logic (Pietrzykowski, 2008, Wang, 2010), or questionnaire results and fuzzy logic

(Pietrzykowski, 2009; Wang, 2010). These results have been helpful in supporting navigation officers' decisions of keeping a safe distance around a ship to avoid collisions. However, this approach has limitations in terms of its ability to consider navigational situations with respect to the surroundings of an individual ship. It is not possible to determine the navigational safety zone.

Hasegawa (1997) proposed calculating collision risks (CR) by using fuzzy logic in the risk assessment of navigational areas. This model relies on the calculated risk quantification that considers the distance to the closest point of approach (DCPA) and the time to the closest point of approach (TCPA). It also considers the decision-making processes in avoiding ship collisions. The limitation of this approach is that the indicated risk only applies to the local vicinity of an individual ship.

Hara (1995) proposed a subjective judgment value (SJ) model to evaluate the ship route area based on navigation officers' perception. This model considers factors such as the distance between ships, the rates of change of the ships' directions, and their approach. In this model, the risks associated with the factors can be quantified by reasoning rules derived from fuzzy membership functions. The value of the reasoning rules was analyzed using a ship handling simulator with navigators serving as experts. Inoue (1997, 2000) has proposed an environment stress (ES) model to evaluate risk of a ship route based on a navigation officer's perception while operating a ship. The risk was calculated by measuring the physical stress on a navigator and using a questionnaire. This risk quantification model considers factors such as the distance between a ship and another ship or an obstacle, the rate of change of the relative directions, and the approaching speed. It is a useful tool to estimate the risk associated with a navigational situation by assessing the navigation officer's difficulty with navigating a ship. As one of the major sources of human error, navigation officers play an important role in navigating ships. However, this type of approach can only be used to evaluate the navigational safety of the surroundings of an individual ship.

In previous studies, these methods have shown to be useful for evaluating the risk associated with ship navigation. However, two additional points regarding the safety evaluation model associated with ship navigational situations have been considered in our model. The first one is that the quantification of risk reflects the navigation officers' perception for estimating risks between ships. At the same time, the evaluation of risk considers various additional factors in managing ship navigation safety in order to support port authorities or vessel traffic service centers. The second is that an algorithm has been developed to evaluate safety for an entire ship route area in real-time. It aims to determine navigational safety zone anywhere along an entire ship route area at a specific time. The aim of this study is to introduce a new model for estimating risk in an entire ship route area in real-time, which reflects navigation officer's perception.

2 A NEW SAFETY EVALUATIN MODEL

A new safety evaluation model is presented in this section for the evaluation of the safety in an entire ship route area in order to support a port safety authority or vessel traffic service center. This model takes into consideration the navigation officer's perception while navigating a ship in addition to a variety of factors. Risk quantification is incorporated in this model, and a new algorithm for evaluating safety in an entire ship route area is developed.

2.1 *Factors as affecting a navigation officer's perception*

A safety index is developed to quantify risks that reveal the perception of a navigation officer depending on a change in the navigational situation. It considers the process of an officer's decision making when encountering other ships as shown in figure 1.

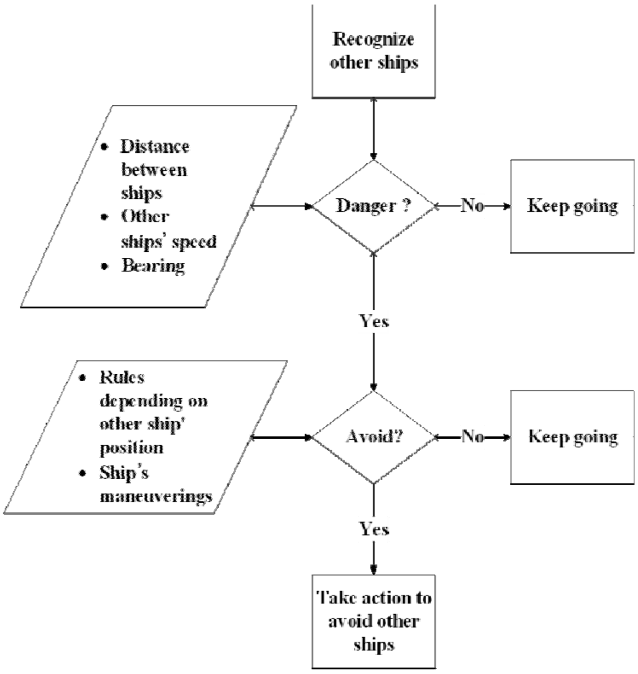

Figure 1. The process of a navigation officer's decision making when encountering other ships

A navigation officer takes action, whether giving way or standing by, after recognizing the risks in a given situation. Decision procedures for avoiding risks are composed of the following steps. At the first step, data is collected to assess the risks presented by other ships. The risks of the encounters are defined based on the difference of direction, distance, and speed. The second step considers the rules and a ship's maneuverability for taking proper action. The factors are designed considering the navigation officer's decision-making process. The model incorporates various factors that affect a navigator's perceptions during ship navigation. Factors are classified according to ship related information (ship type, length of ship), relationship between the ships (relative speed, distance between ships, encounter situations) and environmental situations (time, day). The detailed elements of each factor are shown in Table 1.

Table 1. The design of factors in safety index model

Items	Details	
Type of ship	Container ship, LNG, VLCC, Ferry, Passenger ship, Bulk carrier, Fisher, LPG, PCC, Reefer ship, Tug boat	
Length of ship	Under 100 m, 101–150 m, 151–200 m, 201–250 m, 251–300 m, over 301 m	
Relative speed	0–1.0 k't, 1.1–2.0 k't, 2.1–3.0 k't, 3.1–4.0 k't, over 4.1 k't–	
Distance (L, length of ship)	Under 5L, 6–10L, 11–15L, 16–20L, 21–30L, over 31L	
Encounter situations	Head-on (give-way)	On the centerline of the ship showing from right ahead of 30 degrees abaft the beam of either side of ship
	Crossing on starboard (give-way)	On the starboard side showing from right ahead of 30 degrees to 112.5 degrees
	Crossing on port (stand-on)	On the port side showing from port ahead of 30 degrees to 247.5 degrees
	Overtaking (stand-on)	At the stern showing 67.5 degrees from right aft on each side of ship,
Time (LT, local time)	1st officer's	04:00–08:00, 16:00–20:00
	2nd officer's	00:00–04:00, 12:00–16:00
	3rd officer's	08:00–12:00, 20:00–24:00
Day	Mon., Tue., Wed., Thurs., Fri., Sat., Sun.	

2.2 *Safety index for identifying risks associated with navigation situation*

This section describes how to identify the risk of each factor in this model. A questionnaire is useful tool to measure the degree of risk. In the questionnaire, navigation officers were asked how much each factor affects their perception, using a nine-level evaluation scale (level 1: no influence; level 9: significant influence). The results reflect the navigators' opinions in a quantitative manner that can be incorporated into the safety evaluation model. In this model, each element in question is quantified using equation (1):

$$I_{ij} = \sum_{1}^{N} R_{ij} \times \frac{1}{N} \qquad (1)$$

where:

I_{ij} - average of numerical values for jth element of ith item

R_{ij} - answer value for jth element of ith item (R_{ij} =1-7)

N - number of respondents

i - item number of questionnaire (i =1-8)

j - element number of each item

The results of the quantification of each factor obtained using the questionnaire is shown in Table 2. The safety level reflecting a navigator's perceptions can be calculated using these factors.

Table 2. Risk quantification of each factor determined using questionnaire

Items		Score	
Type of ship		5.3-8.1	
Length of ship		4.5-8.1	
Relative speed		5.1-7.5	
Distance (L, length of ship)		3.8-7.8	
Encounter situations		Passing	Meeting
	Head-on (give-way)	7.9	4.0
	Crossing on starboard (give-way)	7.9	3.2
	Crossing on port (stand-on)	7.3	2.2
	Overtaking (stand-on)	7.4	2.4
Time (LT, Local time)		4.38-5.50	
Day		4.91-5.08	

2.3 *Procedure for evaluating safety in an entire ship route*

Figure 2 shows the stepwise process of the algorithm to evaluate the safety throughout an entire ship route area. Firstly, the whole ship route area is divided into small sections and then ship data are collected for each section. All the ships in each section are regarded as individual ships. In each section, target ship data are collected within a specified range of each ship. The collected ship data are defined as factors in safety index, which includes ship information, the relationship between ships and the environmental situation (Figure 3).

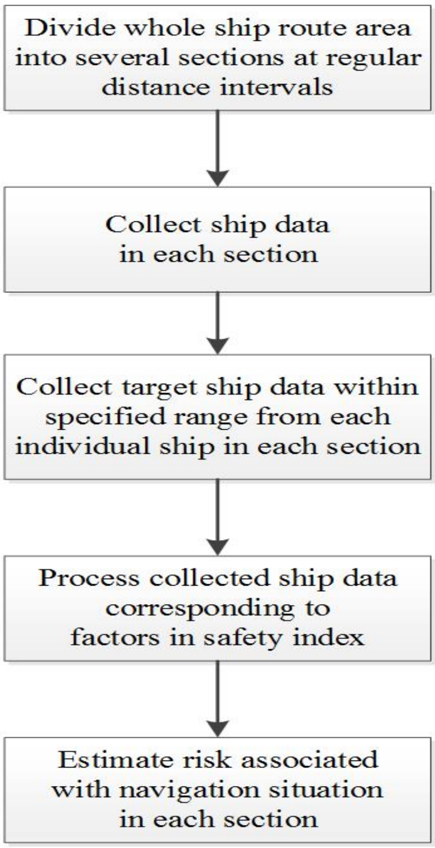

Figure 2. The process of evaluating safety of an entire ship route area

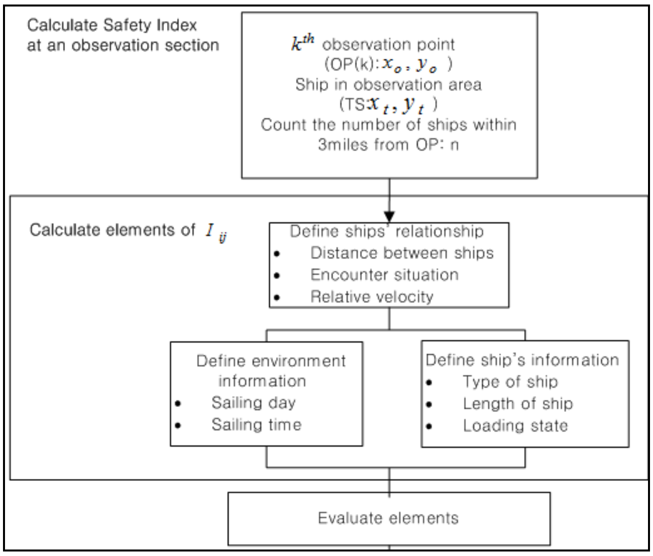

Figure 3. Procedure for calculating safety level in each section

The level of safety in each section is calculated by summing the quantified risks associated with the factors in this model using equation (2):

$$SI = \sum_{1}^{n} \sum_{1}^{i} I_{ij} \tag{2}$$

where:

SI - Safety index for each section

n - Number of ships in each section

I_{ij} - Risk quantification of each element in question

i - item number of questionnaire (i = 1-7)

j - element number of each item

Using the proposed algorithm, the safety level can be calculated for an entire navigational area, which reflects the navigation officer's perception. As a result, a representative value for each section is assigned a safety index.

2.4 *Simulation Method*

In this simulation, automatic identification system (AIS) data have been used to reproduce a marine traffic situation and to evaluate the navigation situation, as shown in Figure 4.

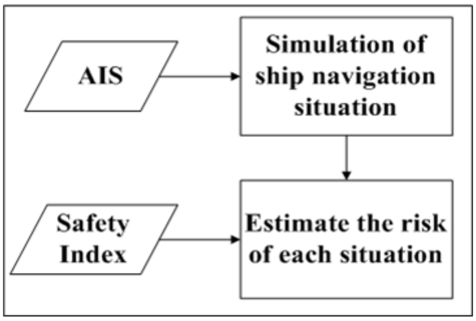

Figure 4. Marine traffic simulation and safety index for evaluating risk of a navigation situation

The AIS is a navigation device that transmits ship information data automatically. The AIS is equipped for domestic ships of over 500 GT and international ships of over 300 GT by the International Maritime Organization (IMO). AIS data are classified as either static or dynamic, and consist of maritime mobile service identity (MMSI) number, ship name, current ship position, speed over ground, and true heading, along with other variables. These data make it easy for the analysis of both the whole traffic flow and individual ship movement.

3 SIMULATION RESULTS

3.1 *Subject observation area*

A simulation was carried out to validate the proposed model for use as a safety evaluation model. It was conducted for Osaka Bay, as shown in Figure 4. Osaka bay is Japan's largest semi-enclosed sea, which is located at the eastern end of Seto Inland. This bay has two entrances for the Osaka/Kobe port areas, which are the Akashi Strait and the Tomogashima Channel. According to the Port Authority of Japan (2010), the area used is latitude N34°14´ to N34°46´ and longitude E134°54´ to E135°26´. This simulation was carried out using AIS data taken from the AIS receiver in Kobe University.

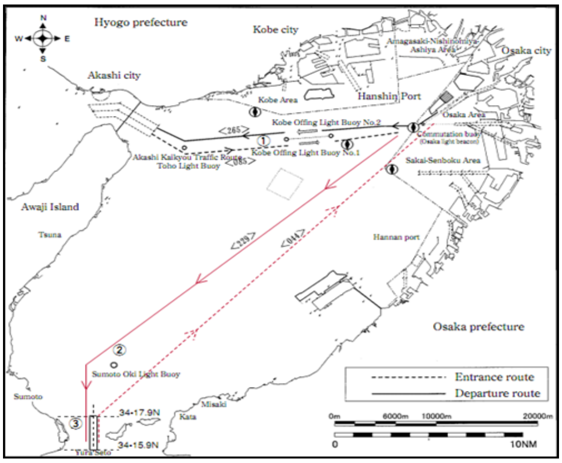

Figure 5. Traffic rules in Osaka Bay (From port authority in Japan, 2010)

Figure 6 shows the trajectories of ships navigating in Osaka Bay based on AIS data beginning at 17:00 for a duration of one hour. In order to evaluate risk in Osaka Bay, the whole ship route area is divided into a 32x32 mesh, with the size of each grid section equal to 1 square mile. At a specific time, ship data are collected using AIS data. The collected data are then distributed to each section. For calculating the relationship risk between ships, data from each ship are collected from within a range of 3 miles. The results are shown in Figures 7 and 8 as an example. Figure 7 shows which area forms a relatively high traffic density area at 19080 sec. The average number of ship encounters within a 3-mile radius is shown in Figure 8. The average number of ship encounters at 19080 sec is about 3 ships. Based on collected data, the safety index for each section is calculated. In the next part, the result of safety evaluation using the proposed model is described.

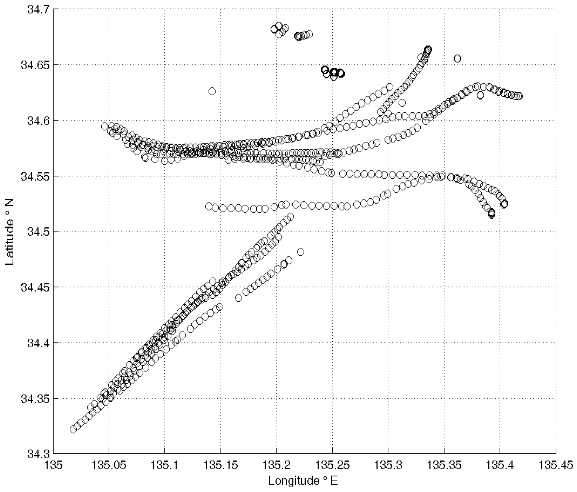

Figure 6. Trajectories of ship passing Osaka Bay from 05:00 to 06:00 on March 1, 2013

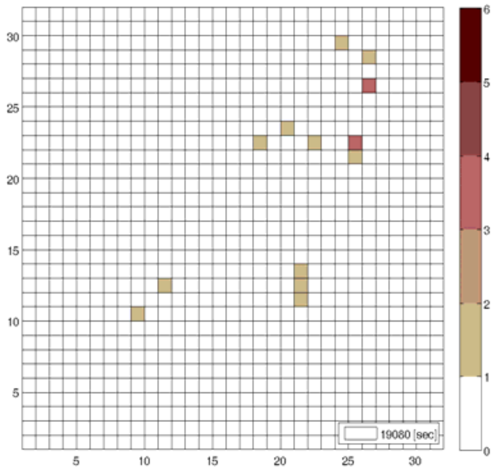

Figure 7. The number of ships in each section at 19080 sec

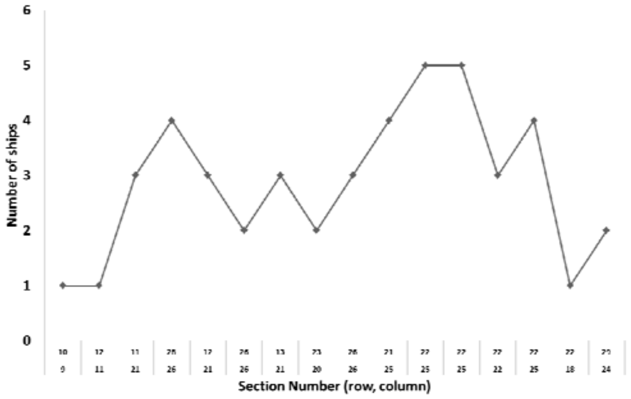

Figure 8. The average number of ships encounters with respect to an individual ship in each section at 19080 sec

3.2 *Results of risk evaluation in Osaka Bay using safety index model*

This part shows the risk calculation results using the proposed safety index model. These results are plotted in color with respect to the level of the safety index. Figure 9 shows the results using the safety index in the entire ship route in Osaka Bay at 19080 sec. The results after two minutes are shown in Figure 10. These results are called a hazard map in this study. A comparison of Figures 9 and 10 shows the safety index changes depending on ship movements in real-time. It illustrates that the navigational safety zone and hazard zone can be determined easily and quickly.

The safety index level at a specific section for a duration of 1 hour beginning at 15:00 is presented in Figures 11 and 12, respectively. In addition, it describes changes depending on the speed and number of ships in these figures. Figure 11 shows the safety index observed at section 27 x 23. The average safety index in this section indicates that it is around 93.2. It shows that the lowest and highest level of safety index is 56.18 and 145.97, respectively.

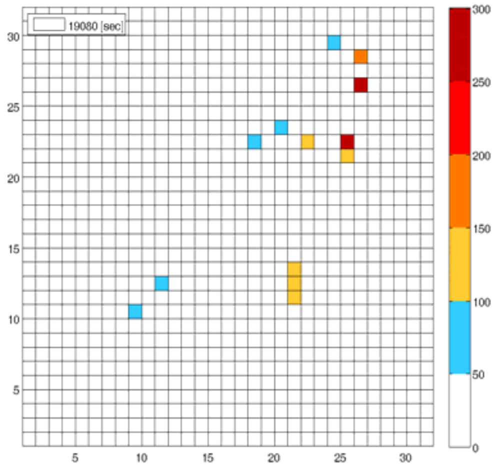

Figure 9. Hazard map according to level of the safety index at 19080 sec

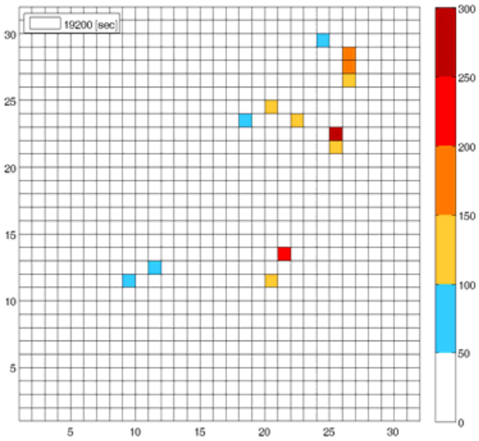

Figure 10. Hazard map according to level of the safety index at 19200 sec

The safety index is affected by the changes in both the number of other ships encountered and their speeds, as shown in Figure 11 as (a), (b) and (c). In these results shown in Figure 11, the number of ships and speed are in inversely proportional to each other. On average, for one-hour duration and with respect to an individual ship navigating through the section, there is one passing ship and about two other ships being encountered. Figure 12 shows the safety index observed in section 16 x 21. The average safety index in this section is approximately 91.2 as shown in figure 12(a). It shows that the lowest and highest level of safety index is 55.14 and 125.44, respectively. In figure 12(b), there are 2 ships passing through this section on average. It shows that the heaviest traffic occurs at 20100 sec, while the highest level of safety index occurs at 20220 sec. In this case, the speed is not affected by the number of ship as shown in figure 12(c).

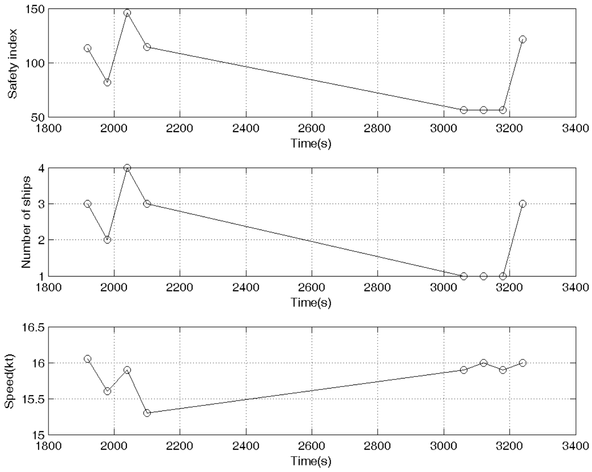

Figure 11. The results for evaluating navigation situation of section 27 x 23 using safety index (a) safety index (b) Number of ships encountering other ships (c) Average speed of ships passing through this section

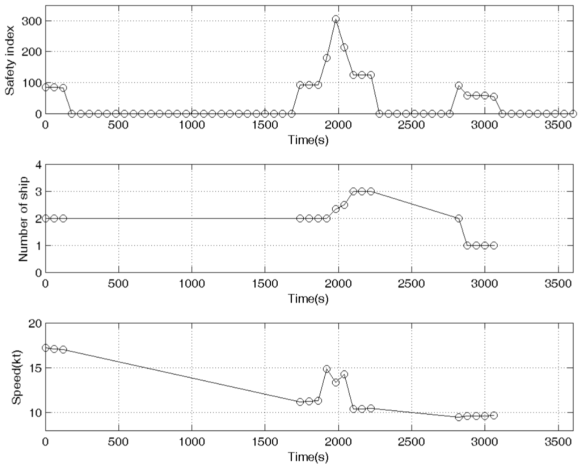

Figure 12. The results for evaluating navigation situation of section 16 x 21 using safety index (a) safety index (b) Number of ships encountering other ships (c) Average speed of ships passing through this section

4 CONCLUSIONS

This paper introduces a new safety evaluation model that can be used to support a port safety authority or vessel traffic service center. This model takes into consideration the evaluation of an entire ship route area at specific time. The risk calculation results reflect a navigation officer's perception using a safety index. This index was established using a questionnaire to obtain input from navigation officers. The algorithm was proposed to calculate the risk throughout whole ship route area. This new safety evaluation model is proposed as a method to estimate risk throughout an entire ship route area in real-time. In order to verify the usefulness of the proposed model, a risk evaluation was implemented for Osaka Bay. The safety index in each section is illustrated in color according to level of risk, which is called a hazard map in this study. This approach allows for visualization of the risk. This model is expected to be able to serve as a new tool for determining hazard zones more quickly and easily than is currently possible with other navigation safety evaluation methods through the centralized management of an entire ship route in real-time,. The procedure developed in this study can be used for supporting the vessel traffic service centers and port safety authorities.

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