



Development of Navigation Safety Analysis for Developing Port Area using Maneuvering Simulation and AIS Data

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Doctoral Dissertation

**Development of Navigation Safety Analysis for
Developing Port Area using Maneuvering
Simulation and AIS Data**

(港湾区域開発のための操縦運動シミュレーションと AIS を活用した航行安全性評価法の開発)

July, 2015

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Dedicated to my beloved: Ni Putu Sri Witari (wife), Putu Gede Bayu Agastya (son), Ni Made Asri Darmapatni (daughter), Komang Ayu Sintawati (daughter), I Wayan Pasek (father), Ni Luh Wayan Tangkis (mother), I Nyoman Windia Gama (father-in-law), Ni Wayan Puspita (mother-in-law)

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Abstract

The number of port throughput in Indonesia increases significantly, in line with the economic growth of the country. Indonesia government has taken a development scheme of main sea-corridor in order to boost the economic growth in the eastern part of the country. The development of the main sea-corridor is also intended to anticipate the increasing number of ship calls, especially in the port of western part of Indonesia. The developing ports may lead a new danger area that becomes obstacle for navigators to steer the ships in the port area. Construction of new wharf in the developing port area not only creates the new danger area but also new route of the ships. The new hazards of ship to wharf collision and ship to ship collision in the area should be properly managed. Therefore, the analysis of navigational safety in a developing port area is essential for the port authority to determine and apply new navigational aids and measures in attempt to prevent accident in the port area.

Tanjung Perak Port Area located in the Madura Straits is considered to be the most important port in Indonesia. The port has strategic role not only for the connection between eastern part and western part of domestic port in Indonesia but also for worldwide connection through international port in Singapore. Number of ship calls in 2008 had been already more than the capacity of the channel. Increasing the number of ship calls and the size of ships entering the port area should be followed by the development of facilities and the improvement of port safety management. The Madura Straits is now in developing stage to increase its capacity from 27,000 to 58,000 ship calls per year. The water depth is dredged from 10.5 m to 14 m. There is also the development of a new port in Lamong Bay located in the west side of the cape of Tanjung Perak Port.

The applications of Automatic Identification System (AIS) data and Maneuvering Modelling Group (MMG) model for navigational safety analysis in port area of Madura Strait have been developed by considering the development of facilities in the area. The purposes of the research studies are summarized as follow: to identify danger areas and propose a method to estimate the width of ship barrier in port area, to develop a method to seek the optimum route with the maximum navigational safety index, to develop a method to estimate the probability of ship on collision courses upon taking astern maneuvers, and to propose a method to estimate collision risk in new two-lane canal in the port area of Madura Strait. In order to achieve the purposes of this research, several chapters have been established.

In Chapter 1, the background consisted of the reasons of the research studies is explored. In addition, the research area in the port area of Madura Strait is introduced. In Chapter 2, AIS data and its application on the proposed methods of ship barrier, optimal route and collision courses probability were presented. The MMG model is described in Chapter 3. Course changing maneuvers and astern maneuvers are simulated using the MMG model and the AIS data are analyzed and treated as the initial condition of the maneuvers at several positions in the research area.

In Chapter 4, the evaluation of navigational safety of ship exiting the new port area has been established. In this study, the subject ship is simulated to avoid collision with entering ship in a danger area. The danger area is identified from the simulation of the entering ship upon taking course changing at the bend of the passage located between the new port and anchorage zones. The method to identify the danger area is proposed as a new method to estimate the dimension of ship barrier in port area. The width of ship barrier in the research area is about $1.12L$ which is less than that introduced by Inoue, $1.6L$, where L is ship length.

In Chapter 5, navigational safety of ship in the existing condition of the research area has been evaluated using Emergency Level (EL) and Environment Stress (ES) methods. New method has been proposed and implemented to seek the optimal route and introduced as Distance Level (DL), Aggregate Distance Level (AgDL), and Average Distance Level (AvDL). The new methods are developed based on the EL and ES methods. The route with the maximum AvDL is selected from probable trajectories. The probable trajectories are estimated using MMG model based on the distribution of yaw rate. The yaw rate is randomly initiated at initial position of turning maneuver between anchorage zones of the research area. The AvDL of the normal trajectory is about 0.2. An optimum trajectory is found with the AvDL of about 0.39.

In Chapter 6, a new Potential Area of Water (PAW) for maneuvering has been introduced. The PAW of ship taking astern maneuvers developed by initial positions of the maneuvers is ordered and the distribution of yaw rate at the initial positions is introduced as the new PAW. The PAW is consisted of probable trajectories of ship upon taking astern maneuvers. The dimension of the PAW is also depending on the speed of ship at the initial position. The number of trajectories entering the opposite lane or crossing the port structure is identified based on the result of the simulation using the MMG model. The maximum safe speed of 6 knots in the research area is suggested as the measure to prevent collisions. Based on the distribution of ships' speed in the area, the probability of ship on collision course upon taking a slow astern maneuver in the port area is about 50%.

In Chapter 7, the collision risk estimation of ship during maneuvering in the bend area of new two-lane canal located at the gate of the research area has been described. A method to estimate the probability of collision in the transition part of bend of the new canal is proposed. The method is developed based on Friss-Hansen model and compared to Kristiansen model. The consequence of collision is estimated using collision energy loss.

In Chapter 8, the discussions regarding the results of research study in Chapter 2 until Chapter 7 has been described. Several suggestion and recommendation have been proposed as measures to prevent collision in the research area. Analysis and application of AIS data and MMG model for navigational safety in the Tanjung Perak Port area have been performed and the further researches have been identified.

Chapter 1

Introduction

1.1 Background

Indonesian ports throughput increases significantly in line with the economic growth of the country. The Ministry of Transportation of the government has taken a development scheme of main sea-corridors in order to anticipate the increasing number of ship calls, especially in the ports of the western part of Indonesia [1]. The development of the main sea-corridor is also intended to boost the economic growth in the eastern part of the country. The developing ports may lead to a new danger area that becomes obstacle for navigators to steer the ships in the ports area. Construction of a new wharf in the developing port area not only creates new danger area but also new route of ships. The new hazards of ship to wharf collision and ship to ship collision in the area should be properly managed. Therefore, the analysis of navigational safety in a developing port area is essential for the port authority to determine and apply new navigational aids and measures in an attempt to prevent accidents in the port area.

Five ports located in four islands of Indonesia are determined as the main sea-corridors as shown in Figure 1-1. Each of the main corridors has two or three loops of operational region. The port in Surabaya, the Port of Tanjung Perak, is the main port of Regional III, the middle region of Indonesia. The port connects two main corridors in the western part, the port of Belawan in the Malaka Strait and the port of Tanjung Priok in Jakarta, and two main corridors in the eastern part, the port of Makasar in Sulawesi and the port of Sorong in Papua. The Tanjung Perak Port located in the Madura Straits, Surabaya,

east of Java, is considered as the most important port. The port is the first main sea-corridor being in development project. It connects not only between the eastern part and the western part of Indonesia but also provides services for international connection between domestic ports and international ports, especially to the ports in Singapore. Moreover, the port has the highest number of destination ports in Indonesia. The port is connected to 30 destination ports.

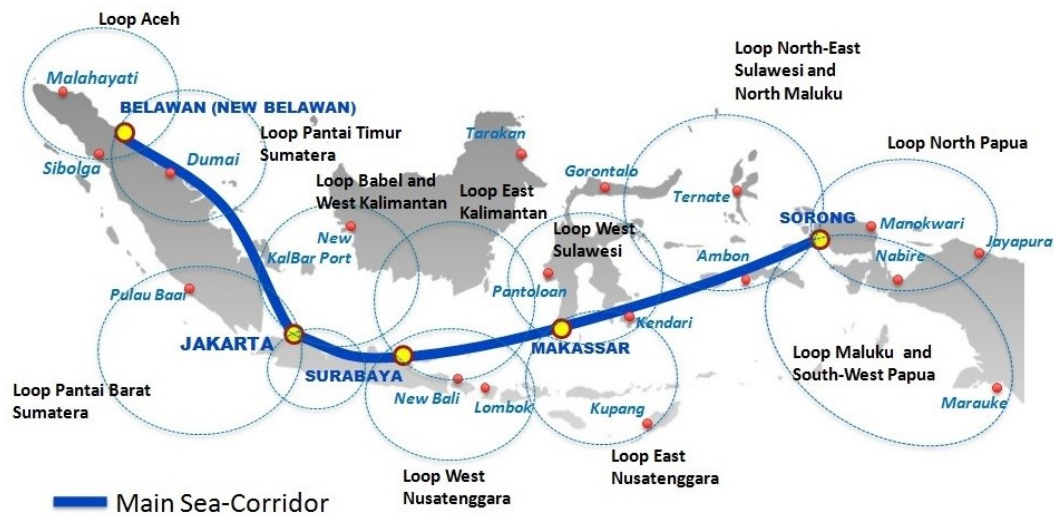


Figure 1-1 Main sea-corridors of Indonesia [1]



Figure 1-2 Area of Tanjung Perak Port [2]

The number of ship calls in Tanjung Perak port increases significantly. The number of ship calls has been already 38,800 ship calls in 2008 and it is predicted that it will be 58,000

in 2030 [3]. On the other hand, the current capacity of canal in Madura Strait is 27,000 ship calls per year. The growth of container handling is about 7% per year, from 1,776,862 in 2005 to 2,407,489 in 2010 [4]. The average waiting time of ship in anchorage area is 3 days. The condition of ship in anchorage area of the port is shown by Figure 1-2. The average number of collisions in the strait is very high, 11 collisions per year. In order to decrease the number of accidents in the developing port area, the improvement of port safety management should be carried out. Therefore, the analysis of navigational safety in the port area is essential for port authority to identify new danger areas and to take preventive actions. The main issues of traffic in the developing port area are summarized as following.

1. The number of collision in the developing port area has been critical.
2. Increasing number of ship calls and the lack of traffic scheme in the developing port area will increase the number of ship collisions.
3. Developing port area creates new danger area and needs new routes of ships in the port area.
4. Difficulty to predict the probability of collision in the area because environment conditions and topography of the developing port area are changing.
5. The analysis of navigational safety in developing port area is essential to propose the implementation of new navigational aids and measures.

1.2 Purpose of the Study

The main purpose of the study is to develop navigational safety analysis for developing port area using maneuvering simulation and Automatic Identification System (AIS) data in the Madura Strait. In this study, the thesis develops navigation safety analysis for ship leaving a new port, ship entering the existing port, ship taking crash astern maneuvers in the developing port area, and ship taking course alteration maneuver in the bend of new canal. New methods are developed to analyse the cases in the port area as following.

1. Method to estimate the barrier of ship in port area. The method is developed using maneuvering simulation and compared to Fujii's model of ship domain [5] and other method of ship barrier in port area introduced by Inoue [6].

2. Method to seek the ship route with the optimum navigation safety-index. New index is developed based on the indices of Emergency Level (EL) and Environment Stress (ES).
3. Method to estimate the probability of ship on collision courses upon taking crash astern maneuvers. The method is developed based on the concept of Potential Area of Water (PAW) for maneuvering introduced by Inoue [7]. New method to develop the PAW is introduced based on the distribution of initial conditions.
4. Method to estimate collision risk in the bend of new two-lane canal. The method to estimate the probability of collision in the bend of the canal is developed based on the Friss-Hansen's model [8] and compared to that proposed by Kristiansen [9].

The distribution of initial condition for ship maneuvering in the port area is analysed from AIS data and possible trajectories of a subject ship are estimated using Maneuvering Modelling Group (MMG) model. The analysis provides some suggestions and recommendations for the port authority to apply new navigational aids and measures as an attempt to prevent accidents in the developing port area.

1.3 The Area and Scope of Study

The study area is the ports area in the Madura Straits. In this area, there are several ports located in 2 regencies and a city, including the Regency of Gresik, the Regency of Lamongan and the City of Surabaya. The Tanjung Perak port is operated by PT Pelindo III, the national marine transportation company of the Indonesian Government. The ports located in Gresik Regency are operated by some public companies such as the ports of PT Maspion and PT Smelting. The Port of Gresik is a port of the local government. The ports of several state companies including PT Petro Kimia Gresik and PT Semen Gresik are also located in this region. The new port in Lamong Bay called Lamong Bay Port, is an extension of the Tanjung Perak Port of Surabaya, and is managed by the PT Pelindo III. In the island of Madura, there is only a port for ferry. The utility of the port has been reduced by the operation of a new bridge connecting between Java Island and the Madura Island.

The selected area is located between 112°38'47" (112.64633) to 112°46'17" (112.77133) of eastern longitude and -7°8'24" (-7.13733) to -7°13'35" (-7.22633) of south latitude as shown in Figure 1-3. The new two-lane canal is located in the north side of the

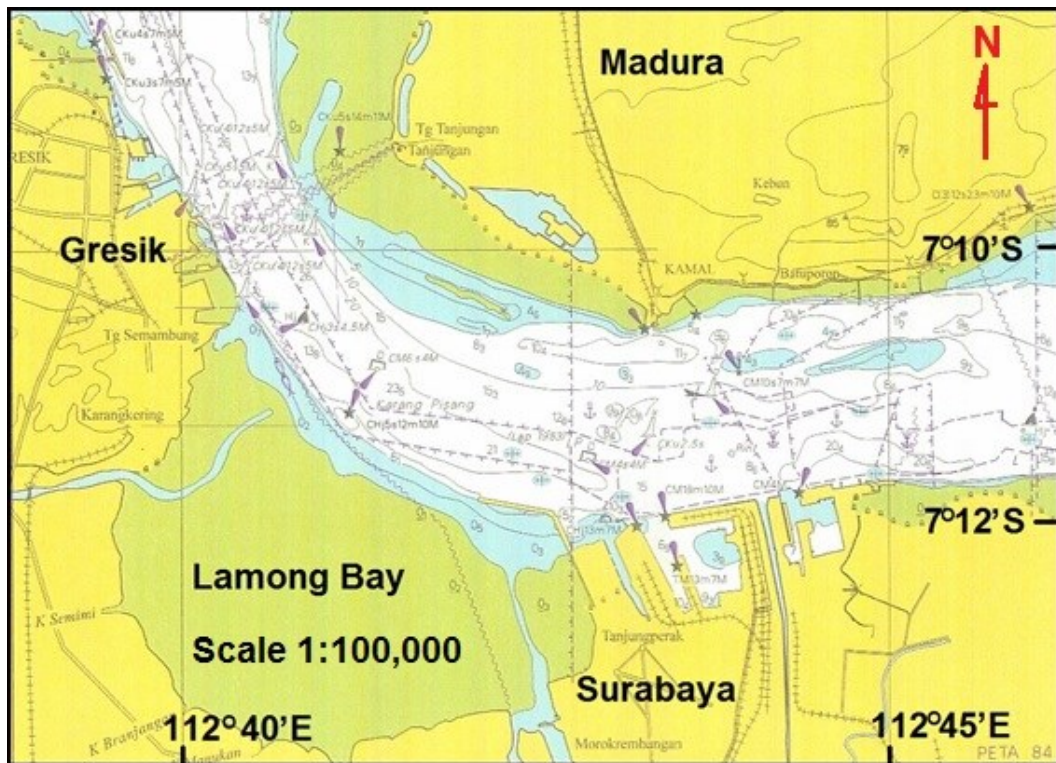


Figure 1-3 Study area of research

area as an entering and leaving gate of the port area. The construction of new port in the Lamong Bay has changed the pattern of the ships route in the area. River floods and mud flows in the area caused the shallow sea depth in anchorage area. In addition, the increasing of ship calls made some ships to anchor out of the anchorage area.

Topographical condition, external environment, ship traffic, and ship condition are the four variables which are considered in the analysis of navigational safety. The development of Tanjung Perak Port as one of the main sea-corridors will cause the increasing of ships traffic density in the Madura Strait. The operation of new port in the strait to increase the capacity of the existing port is also considered as a new topographical condition. Accordingly, the analysis of navigational safety in the new topographical condition of the port area is important to be carried out. In addition, the effects of the external environment including wind, current, and shallow water and the condition of ships are also considered. The environment effects are implemented as external forces and moment in the Maneuvering Modelling Group (MMG) model. The application of the MMG model is needed to estimate possible trajectories for the analysis of navigational safety in the research area.

The Automatic Identification System (AIS) is one of shipborne navigation equipment and system intended to improve maritime safety. The usage of AIS data is widely utilized by

researchers on the fields of maritime safety, such as traffic pattern analysis [10], mitigation and evacuation for tsunami [11], marine pollution analysis [12], and the risk assessment of anchor dredging [13]. In this study, the AIS data in the Madura Strait are utilized for navigation safety analysis. The AIS data is analysed to estimate of initial conditions of ships maneuvering in the research area. The distributions of initial conditions analysed from AIS are implemented on the MMG model to estimate possible trajectories.

The simulation of possible trajectories is introduced as the proposed methods on the analysis of ships barrier, navigational safety indices, and collision probability. The danger area of the developing port area is identified and a new method to estimate ships' barrier in the danger area is introduced. In addition a new method of navigation safety-index method is introduced. The new safety index is developed based on the methods of Emergency Levels (EL) and Environment Stress (ES). The new method is proposed as a method to seek the optimum route. The possible trajectories are also implemented to estimate the probability of ship on collision course upon taking crash astern maneuvers and the probability of ship collision in the bend of new canal.

In Chapter 2, the analysis of AIS data in the Madura Strait are presented. The distributions of maneuvering initial conditions including the yaw rate and drift angle are described in this Chapter. In Chapter 3, the MMG model is introduced and the program of ship maneuvering simulation is developed on MATLAB program based on the MMG model. In Chapter 4, the distribution of ship trajectories predicted by the MMG model is carried out. The possible trajectories of a subject ship is analysed based on the distribution of initial yaw rate and drift angle in the port area. The barrier of ship entering the port area was estimated and treated as a danger area in the area. A safe route is suggested as the passage to exit the new port area and avoid the danger area.

Secondly, a new method to analyse the navigational safety is implemented on the fairway located between anchoring zones is proposed in Chapter 5. In this chapter the Emergency Level (EL) and Environment Stress (ES) of subject ship taking turn maneuvers between the anchorage zones is analysed. A method to detect obstacles is proposed by using the current position and the course of the subject ship computed in the MMG model. By the method, the obstacles including the water lines of the ship in the area and the virtual lines of shallow water as well as the virtual lines of the boundary of anchorage zones is detected. The shortest stopping distance is estimated using the International Maritime Organization (IMO)

equation. New indices of navigation safety including the Distance Level (DL), the Aggregate Distance Level (AgDL), and the Average Distance Level (AvDL) are proposed and implemented in the research area to seek the optimal route.

Thirdly, in Chapter 6, the subject ship is simulated in the research area to take crash astern maneuvers and the probability of ship on collision course upon taking crash astern maneuvers is estimated. The method is implemented by considering the new topographical condition of the area due to the operation of the new port of Lamong Bay. The method is developed based on the concept of the potential area of water (PAW) for maneuvering. A new PAW is introduced which is developed not only by the positions of the maneuvers are ordered but also by the distribution of yaw rate at the positions. The distribution of ships' speed in the area is also analysed from AIS data and the maximum safe speed to take the maneuvers is proposed as a measure to prevent collision at the new topographical condition.

Furthermore, in Chapter 7, the collision risk estimation of ship during maneuvering in new two-lane canal located at the gate of the research area has been described. A method to estimate the probability of collision in the bend of new canal is proposed. The method is developed based on Friis-Hansen method [8] and the result is compared to that resulted from Kristiansen method [9]. The consequence of collision is estimated using collision energy losses.

Finally, in Chapter 8, discussion and conclusion are summarized from the previous chapters. Measures including suggestion and recommendation for port authority are proposed to improve the navigational safety of ship in the research area. New methods have been developed and proposed to analyse and evaluate the navigational safety in the developing port area.

Chapter 2

Automatic Identification System (AIS)

2.1 Introduction

In 2000, the International Maritime Organization (IMO) adopted the regulation V/19 of the Safety of Life at Sea (SOLAS) [14]. Based on the regulation, all ships that the tonnage are at least 300 gross tonnage which are engaged on international voyages and cargo ships of 500 gross tonnage and upwards that are not engaged on international voyages as well as passenger ships irrespective of size should be fitted with an automatic identification system (AIS). The system should automatically provide data about the ship to other ship and coastal authorities as represented by Figure 2-1.

The Regulation 19, Chapter V, Paragraph 2.4.5 of SOLAS 2002 requires that shipborne AIS shall [15]:

1. provide automatically information, including the ship's identity, type, position, course, speed, navigational status and other safety-related information to appropriately equipped shore station, other ships and aircraft;
2. receive automatically such information from similarly fitted ships;
3. monitor and track ships; and
4. exchange data with shore-based facilities;
5. in cases where the international agreements, rules or standards provide for the protection of navigational information, the requirements of this paragraph shall not be applied
6. AIS shall be operated by taking into account the guidelines adopted by the organization.

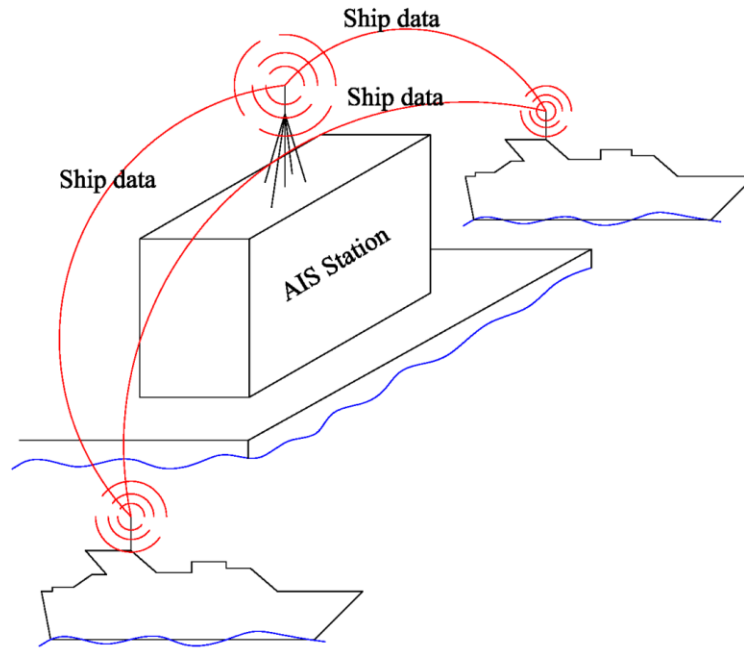


Figure 2-1 AIS data transmission

Data provided by AIS is intended to improve the quality of information available for the officers of the watch (OOW) who are both on board of ship and shore surveillance station such as the vessel traffic service of port authority and other institution. The objective of the AIS is to enhance the safety of life at sea, the navigation safety and efficiency and the marine environment protection.

2.2 The Usage of AIS Data

Several studies using AIS data have been conducted and implemented in several areas around the world by other researchers, such as the use of AIS data in relation to the planned route and navigational information for the assessment of the safety and efficiency in Osaka Bay. In that research, collision avoidance was calculated using dynamic programming [10]. Research on the traffic density within the Osaka Port area using AIS data has also been conducted in order to develop an assessment method for ship evacuations in response to pending tsunamis by implementing a general discrete event simulation [11]. This determined the best distance between ships and the allowable number of ship transits. The implementation of AIS for the evaluation of marine traffic safety in the Malacca Strait was

performed by other researchers based on the analytic hierarchy process [16]. Using this method, the danger scores for a subject ship in the area were calculated many time.

A quantitative assessment method for marine traffic safety in the Gulf of Finland on the basis of AIS data was developed based on another approach derived from a gas molecular collision model combined with vessel domain theory, which takes into account the vessel dynamics and uses advanced statistical and optimization methods such as the Monte Carlo and genetic algorithms [17,18,19].

AIS data in the Madura Strait have been analysed by Mulyadi et al [13] to estimate the probability of dragged anchor on subsea pipeline. In this study, the AIS data in Madura Strait are utilized for other purposes. The implementation of AIS data in Madura Strait on the development of methods to analyse the navigational safety in the port area is presented in this study as an attempt to determine measures for accident prevention. The study includes the development of method to estimate ships barrier in port area, to seek the optimum route, to estimate the probability of ship on collision course upon taking crash astern maneuvers, and to estimate collision risk in the new canal.

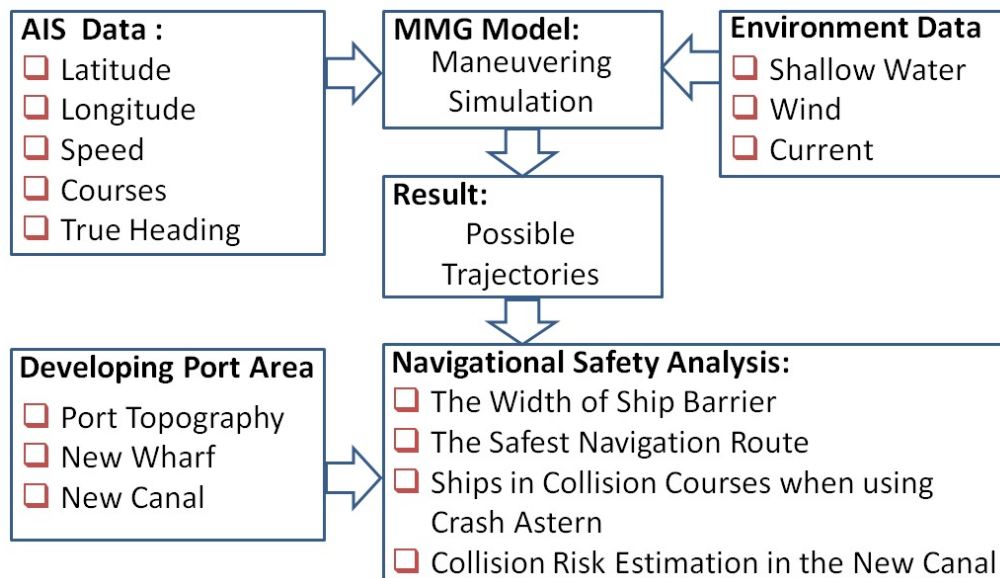


Figure 2-2 Implementation of AIS data on the development of navigation safety analysis using MMG model

The methodology for the implementation of AIS data for the navigational safety analysis based on Maneuvering Modelling Group (MMG) model is shown by Figure 2-2.

2.3 AIS Data Analysis

Analyses of AIS data are presented in the following sub-sub sections. The analyses are consisted of four parts implemented in Chapter 4 to Chapter 7. The AIS data for Chapter 4 are taken from an entering ship for 15 minutes from latitude -7.16600 to latitude -7.18963. The AIS data from 25 ships belonging to class C upon entering the latitude of -7.16600 were analyzed to estimate distribution of drift angle and implemented in Chapter 5. Distribution of yaw rate is estimated in the chapter using the method of small zigzag maneuver. Another approach of AIS data analysis to estimate the distribution of yaw rate is implemented in six zones of the research area, in Chapter 6. The method is developed by comparing trajectories and yaw angle time series of a subject ship to those of ship belonging to the same class taken from AIS data. Distribution of yaw rate in the area of new two-lane canal is also presented for Chapter 7.

The AIS data for the Madura Strait were obtained from the receiver installed at a laboratory in Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia, under cooperation between Kobe University and ITS. The dynamic data of AIS, including the true heading angle, course on the ground (COG), and speed on the ground (SOG), and static data of latitude and longitude were implemented in this study. The AIS data used in Chapter 4 to 7 are presented as following.

2.3.1 AIS Data Analysis for Estimation of Ship Barrier

The ship barrier estimation method was developed using maneuvering simulation based on the distribution of initial ship conditions in the research area. The width of ship barrier entering the area is estimated to be avoided by a ship leaving a new port. The initial conditions of entering ship were analyzed based on the AIS data. An entering ship on January 1, 2011 was selected and the drift angle and yaw rate of the ship was analyzed. The trajectory of ship leaving the new port of Lamong Bay was simulated using Maneuvering Modelling Group (MMG) model and the navigational safety of the ship was analyzed.

The trajectory of the entering ship is shown by Figure 2-3 in blue. The data of the trajectory were selected for 900 s from latitude S7.166° to S7.187°, from the entering of

anchorage area to the entering of the new port. The latitude positions are respectively represented in the figure by 0 and -2000 of x_0 positions.

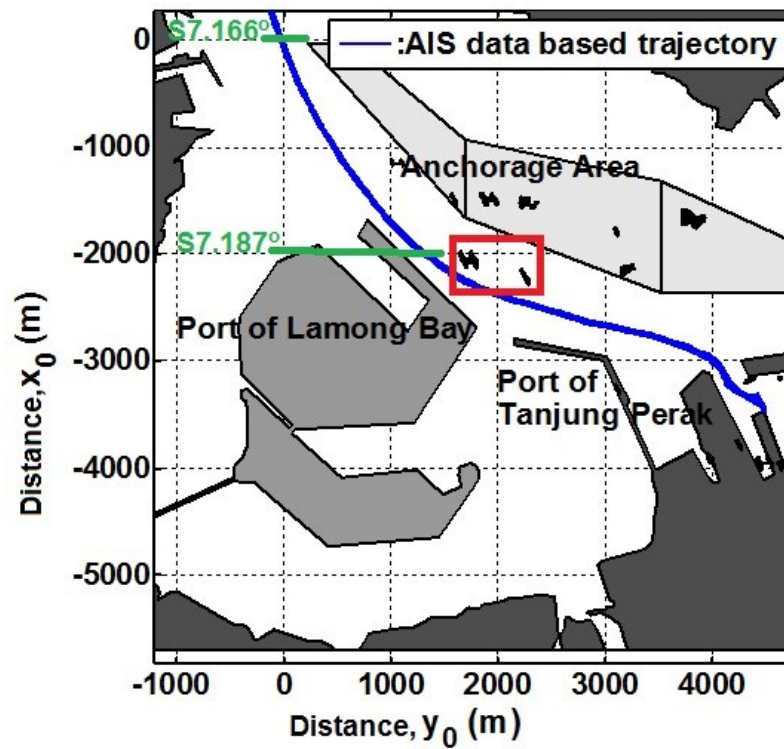


Figure 2-3 Trajectory of an incoming ship

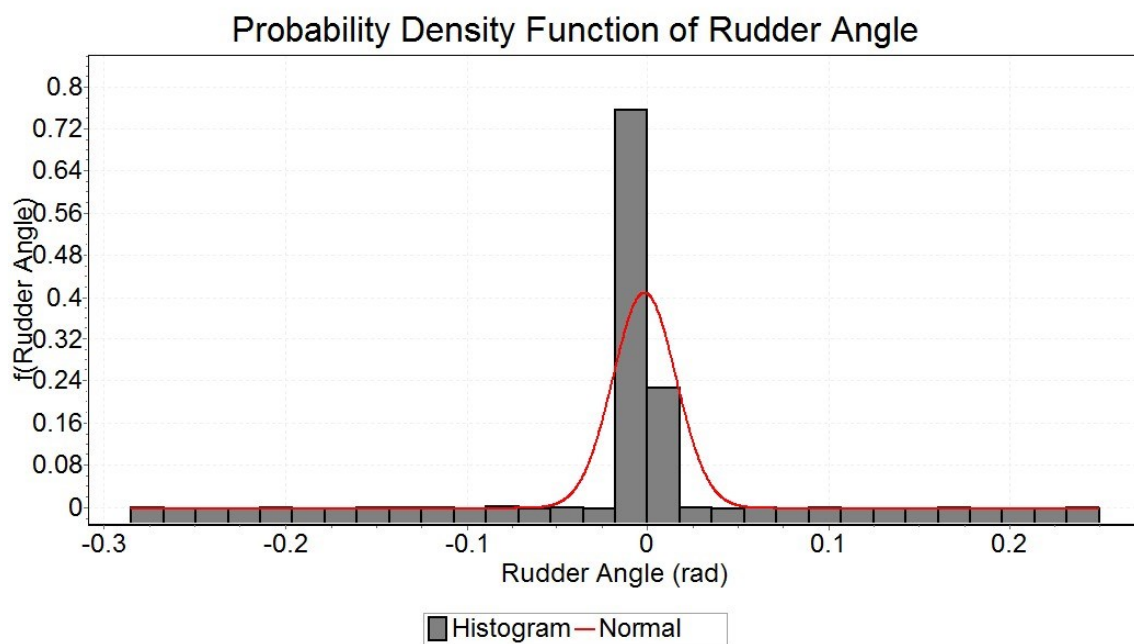


Figure 2-4 Distribution of rudder angle

The figure also shows two ships anchoring out of the anchorage area along the fairway. The ships are shown by the red box in the figure. The selected data of the entering ship were interpolated every 1 second and the yaw rate was determined by change of the true heading. Drift angle was calculated as the true heading minus the course over ground (COG). The interpolated yaw rate is shown in Table 2-1 in every 60 s.

The trend of rudder angle of the ship along the selected trajectory was predicted using the linear maneuvering model. The prediction method was introduced by Nakano [20]. The K' and T' correlation used for the implementation of the method was taken from Kobayashi [21]. The distributions of rudder angle, yaw rate, and drift angle fit with normal distribution as shown in Table 2-2. Rudder angle distribution is shown by Figure 2-4.

Table 2-1 Interpolated AIS data

Time (s)	Latitude^{*)}	Longitude	COG (°)	Heading (°)
0	-7.16600	112.67886	160	157
60	-7.16915	112.68019	157	154
120	-7.17101	112.68103	155	150
180	-7.17272	112.68186	152	150
240	-7.17519	112.68319	149	146
300	-7.17675	112.68403	147	145
360	-7.17814	112.68486	147	142
420	-7.18018	112.68639	142	140
480	-7.18130	112.68803	142	139
540	-7.18267	112.68886	141	137
600	-7.18453	112.69019	136	133
660	-7.18558	112.69106	133	130
720	-7.18661	112.69272	130	126
780	-7.18803	112.69419	125	123
840	-7.18890	112.69506	122	120
900	-7.18963	112.69672	119	115

*) - : southern hemisphere

Table 2-2 Distributions of conditions

Conditions	Distributions	Parameters	
Rudder Angle (rad)	Normal	Mean	-0.001920
		Standard Deviation	0.005760
Yaw Rate (rad/s)	Normal	Mean	-0.000160
		Standard Deviation	0.001200
Drift Angle (rad)	Normal	Mean	0.020000
		Standard Deviation	0.120000

2.3.2 AIS Data Analysis for Development of Navigation Safety-Index

New navigation safety-index method was developed based on distributions of drift angle and yaw rate at the initial position of entering anchorage zones, at latitude $S7.166^\circ$. The trajectory of a ship entering the area in January, 2011 is shown in Figure 2-5.

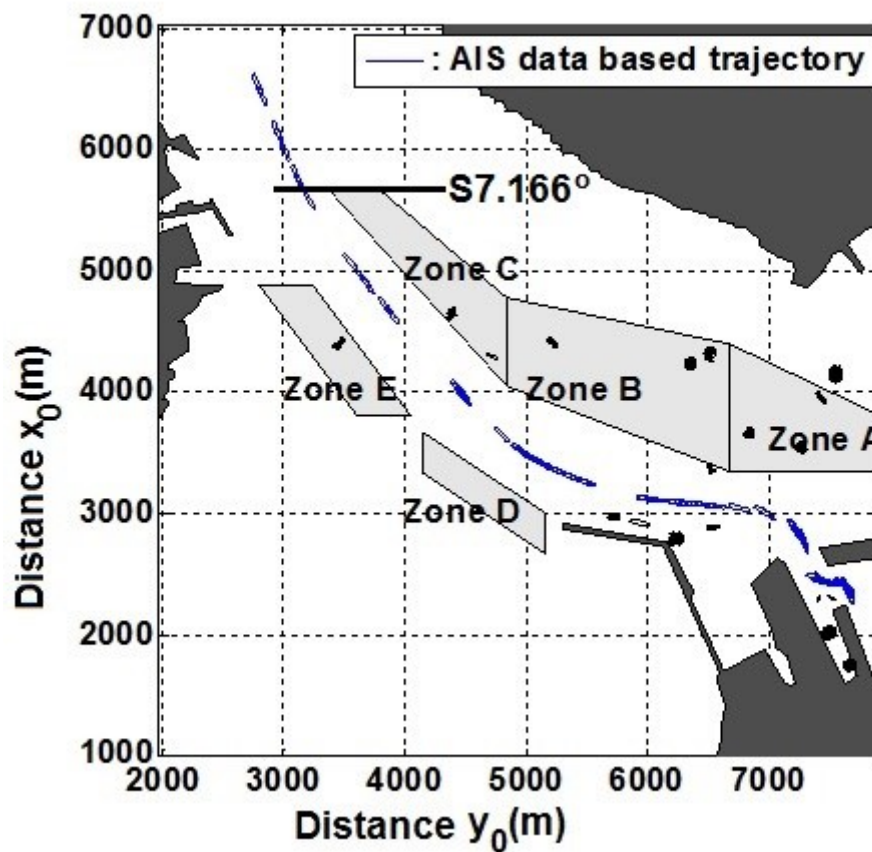


Figure 2-5 Trajectory of an incoming ship between anchorage zones

The distribution of drift angle of ships at the position was taken from the AIS data from January 1, 2011 to January 7, 2011. The average number of entering ship per day was 42 and the number of recorded ships belonging to class C, the ships having length from 150 m to 200 m, at the position was 25. The distribution of yaw rate at the position was estimated using small zigzag maneuvering simulations. The comparison of trend of yaw angle derived from AIS data and those resulted from the simulations is shown in Figure 2-6. The amplitude of trend of yaw angle of the entering ship before passing the initial position almost fit with the simulation result of 2°/-2° zigzag maneuver. This method is still unsatisfied because the trend of yaw rate for the first 300 s derived from AIS data is different with that of the simulation.

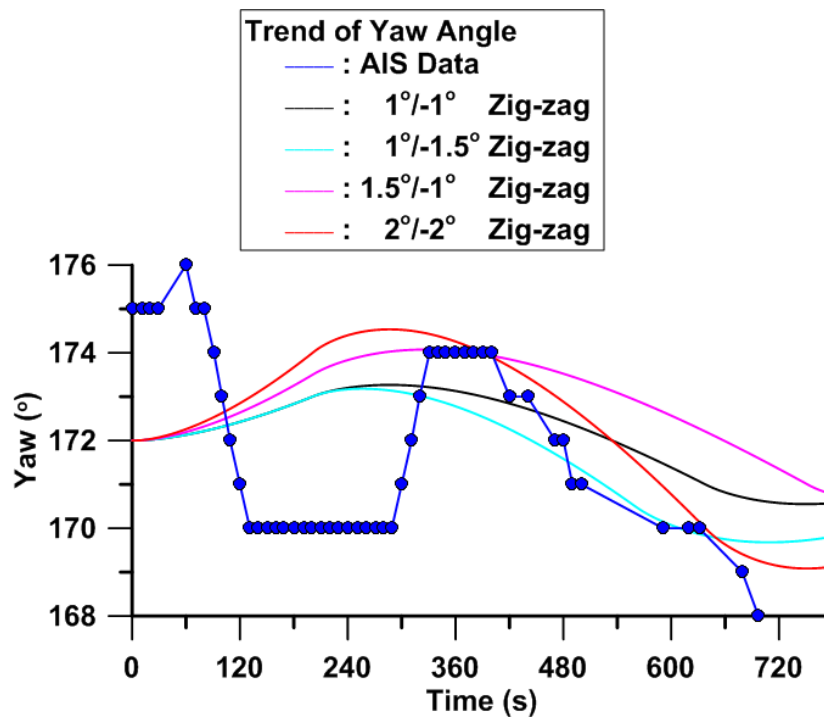


Figure 2-6 Comparison of the trend of yaw angle

Table 2-3 Distribution of initial conditions upon entering the anchorage zones

Initial Conditions	Distribution Name	Distribution Parameter	
Drift angle, β (rad)	Normal	$\mu = -0.022830$	$\sigma = 0.040130$
Yaw rate, r (rad/s)	Uniform	$a = -0.000360$	$b = 0.000280$

The distribution of yaw rate at the initial position was analyzed from the trend of yaw rate of 2° - 2° zigzag maneuver. The drift angle and yaw rate distributions were presented by Table 2-3. The drift angle fits to normal distribution with the mean of -0.022830 and the standard distribution of 0.040130. The yaw rate distribution is uniform with the minimum of -0.000360 and the maximum of 0.000280.

2.3.3 AIS Data Analysis for the Estimation of Ship on Collision Courses

The probability of ship on collision courses upon taking crash astern maneuvers was estimated based on a new Potential Area of Water (PAW) for maneuvering. The new PAW was developed based on distribution of yaw rate at the position when the maneuver is ordered. The distribution of yaw rate in each area was estimated by the trend of yaw angle of a subject ship in the area simulated using Maneuvering Modelling Group (MMG) model.

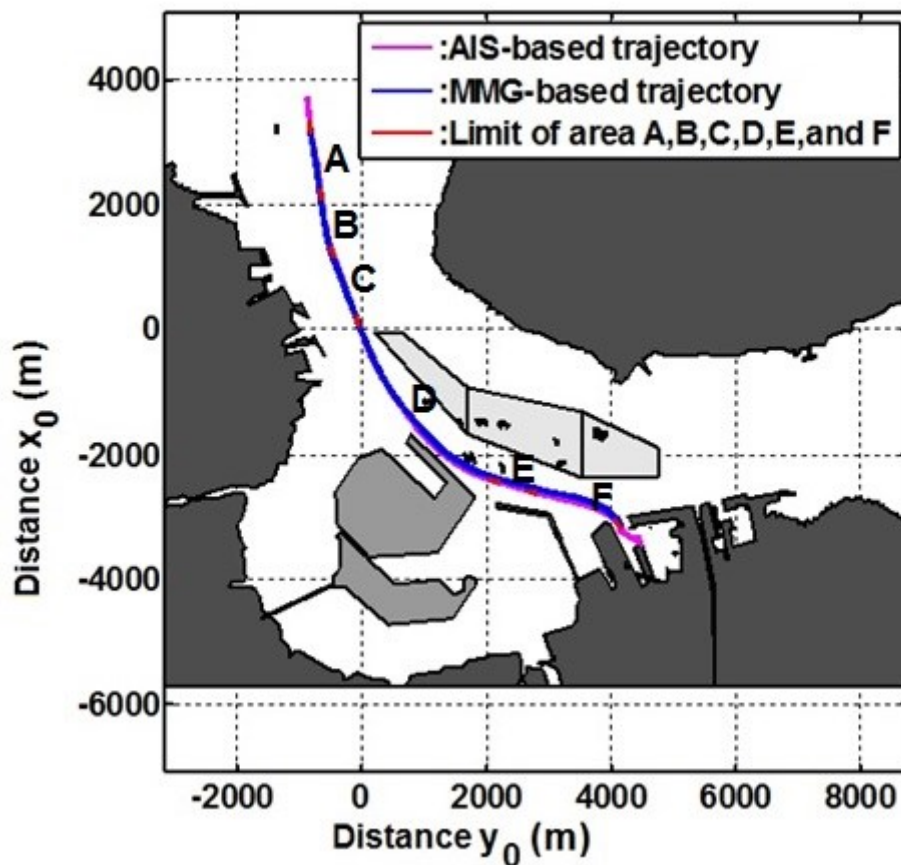


Figure 2-7 Trajectory of subject ship

The research area divided into six zones was shown in Figure 2-7. The trajectory and the trend of yaw angle of the ship in the areas plotted from AIS data were compared to those resulted from the simulation as shown by Figure 2-7 and Figure 2-8, respectively.

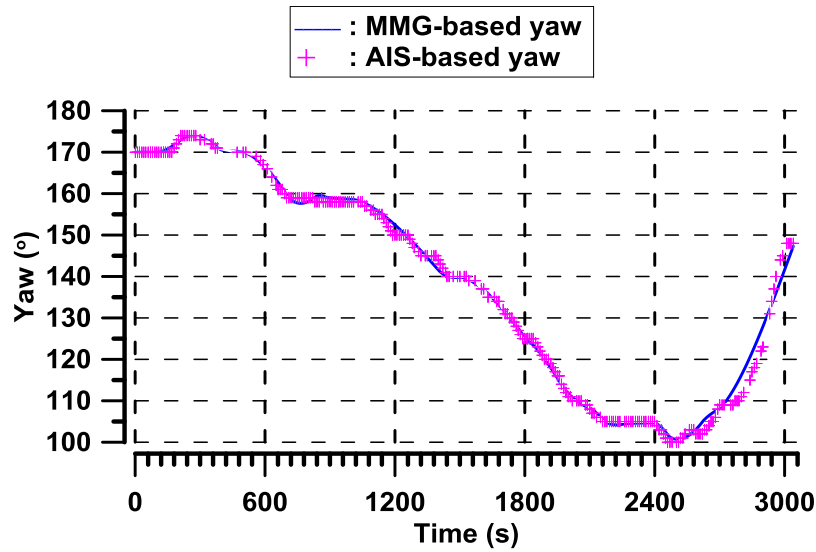


Figure 2-8 Time series of yaw angle

Table 2-4 Distribution of yaw rate in the six zones

Area	Distribution of Yaw Rate	Distribution Parameters	
		(rad/s)	
A	Normal	$\mu = 0.000049$	$\sigma = 0.000408$
B	Uniform	$a = -0.001410$	$b = 0.000153$
C	Normal	$\mu = 0.000065$	$\sigma = 0.000389$
D	Normal	$\mu = 0.000794$	$\sigma = 0.000350$
E	Uniform	$a = -0.000625$	$b = 0.000368$
F	Uniform	$a = -0.001480$	$b = 0.002390$

The distributions of yaw rates in the six zones of the research area fit to normal and uniform distributions. The mean μ , and the standard deviation σ , of the normal distribution, as well as the minimum a , and the maximum b , of the uniform distribution are shown in Table 2-4. The number of ships on collision courses upon taking crash astern maneuvers was estimated from the probability of ships on collision courses and the number of ship calls. The probability also depends on distribution of ships speed in the zones. The number of ship calls and the distribution of ships' speed are shown in Figure 2-9 and Table 2-5, respectively.

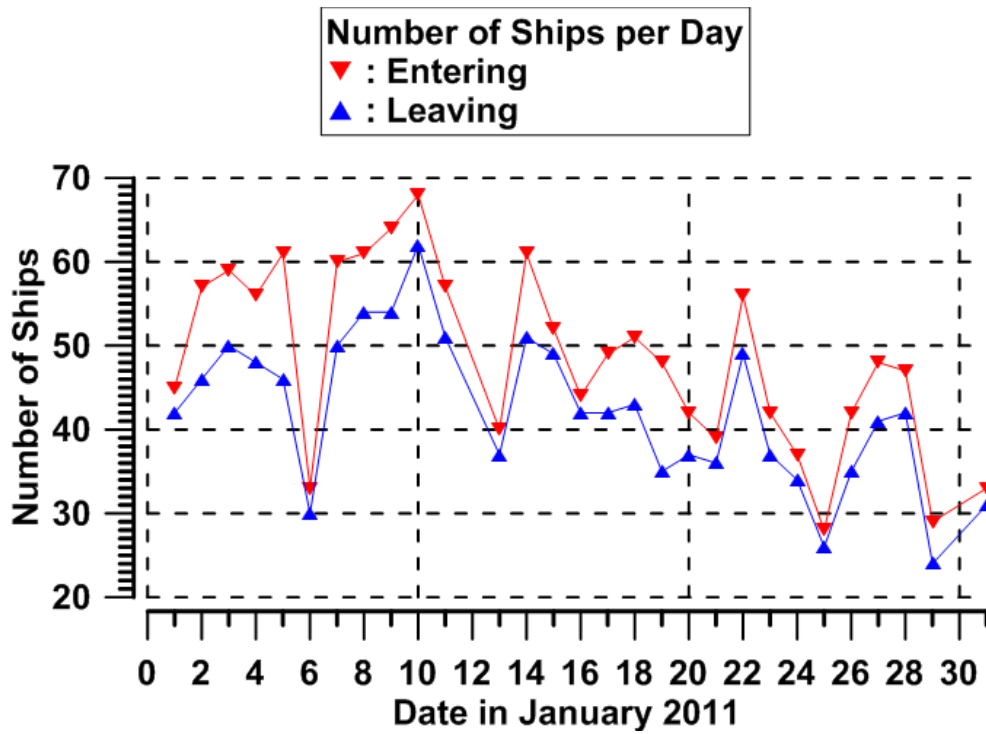


Figure 2-9 Numbers of entering and leaving ship in the research area

Table 2-5 Ships' speed distribution of 25 ships belonging to class C

Area	Distribution	Parameter of Distribution	
		Mean (kts)	Standard Deviation (kts)
A	Normal	9.8	3.4
B	Normal	9.7	3.4
C	Normal	9.5	3.1
D	Normal	7.7	3.9
E	Normal	6.1	2.8
F	Normal	5.7	2.5

2.3.4 AIS Data Analysis for the Estimation of Collision Risk in New Canal

The data were implemented to propose a new method for estimating the probability of wrong maneuvers based on the distribution of yaw rate in the canal. The yaw rate of ship maneuvering at the research area was calculated from the AIS data. The AIS data presented in

this paper are intended for calculating the probability of collision in bend part of the new canal. The AIS data as on January 1, 2011 were analyzed for this study. The position of the bend of the canal was obtained as latitude -7.125 which is the position 7° 7'30" S. The minus sign on the geographical coordinate indicates the position is in the southern hemisphere and the unit is degree. The average numbers of ships per day voyaging in the canal between latitudes -7.083 and -7.137 which are 7° 4' 59"S and 7° 8' 13"S, respectively (derived from the AIS in January 2011) are presented in Figure 2-9.

The new canal is intended to support the development of the new Lamong Bay port for the incoming and outgoing passages of ships. The position of the new canal is shown in Figure 7-1 of Chapter 7. The AIS data at the position of the bend of the new canal were predetermined at a location between latitudes -7.124 and -7.126, as listed in Table 2-6. The average and standard deviation of the normal distribution of the AIS data at the bend of the new canal are listed in Table 2-7.

Table 2-6 AIS data at the -7.125 latitude

MMSI	β (rad)	r (rad/s)	U_0 (kts)
210383000	-0.03143	0.00025	17.0
211119000	0.04889	0.00058	10.3
351436000	0.01746	0.00000	12.7
370017000	0.03968	0.00146	8.0
370390000	0.00000	-0.00003	11.4
372781000	-0.00349	0.00011	8.6
441314000	-0.00349	0.00008	10.3
525015574	-0.01135	0.00000	6.4
525019298	0.01833	-0.00132	8.5
525025041	-0.02095	-0.00023	11.9
525025043	-0.04714	0.00010	11.4
525025062	-0.08730	-0.00044	12.5
538003585	-0.02444	0.00006	9.8
538003672	-0.05238	0.00041	10.6
636091449	0.00635	0.00000	10.1

Table 2-7 Data distribution at -7.125 latitude

Variables	Average	Standard Deviation
Drift angle (rad)	-0.01008	0.03252
Yaw rate (rad/s)	0.00007	0.00058
Speed (kts)	10.6	2.5

Chapter 3

Maneuvering Modelling Group (MMG) Model

3.1 Introduction

The standards for ship maneuverability have been adopted by the International Maritime Organization (IMO) as Resolution A.751(18), on November 4, 1993 [22]. The resolution is about Interim Standards for Ship Maneuverability for ships with traditional propulsion and steering system. The standards were recommended by the Maritime Safety Committee (MSC) based on recognizing that the maneuvering capability of ships has an important contribution to the safety of navigation. Based on the resolution, following methods can be applied to demonstrate compliance with these standards.

1. At the design stage, scale model tests and/or computer prediction using mathematical models can be performed and the results should be validated by conducting full-scale trials.
2. The compliance with the standards can be demonstrated based on the results of full-scale trials conducted in accordance with the standards. The administration should take remedial action if a ship is found in substantial disagreement with the standards.

Computer prediction using mathematical model is generally known as the Maneuvering Modelling Group (MMG) model [23]. The MMG model is one of methods used to predict ship maneuverability. The MMG model is a nonlinear mathematical model which involves several hull, rudder, and propeller coefficients. On the other hand, the K-T model is

a linear mathematical model which involves the variables of rudder angle and the yaw rate of ships using two parameters of K and T [20]. Another method of Computer Fluid Dynamics (CFD) is recently used to predict maneuverability of ship.

The criteria used for the compliance of the standards, especially for the criteria number 3 and 4 was renewed by annex 5 of IMO Resolution MSC.137(76), 2002. The maneuverability of ship is considered satisfactory by using the criteria as below.

1. For turning ability, the advance should not exceed $4.5L$ and the tactical diameter should not exceed $5L$.
2. For initial turning ability, with the application of 10° rudder angle to port/starboard, the ship should not have travelled more than $2.5L$ by the time the heading has changed by 10° from the original heading.
3. For yaw checking and course-keeping abilities, the criteria are as below:
 - a. The value of the first overshooting angle in the $10^\circ/10^\circ$ zigzag test should not exceed: 10° for L/V is less than 10 s; 20° for L/V is 30 s or more; and $(5+0.5(L/V))$ degrees if L/V is 10 s or more, but less than 30 s.
 - b. The value of the second overshooting angle in the $10^\circ/10^\circ$ zigzag test should not exceed: 25° for L/V is less than 10 s; 40° for L/V is 30 s or more; and $(17.5+0.75(L/V))$ degrees if L/V is 10 s or more, but less than 30 s.
 - c. The value of the second overshooting angle in the $20^\circ/20^\circ$ zigzag test should not exceed 25° .
4. For stopping ability, the track reach in the full astern stopping test should not exceed $15L$. The administration may modify this value for ships of large displacement, but should not exceed $20L$.

Where L is the length between perpendiculars (L_{pp}) in m and V is the 90% of ship speed which corresponds to 85% maximum of engine output in m/s.

In this study, the MMG model was implemented to simulate probable trajectories of ship according to distribution of initial conditions of ship maneuvering in the research area. The initial conditions were analyzed from AIS data. The possible trajectories of turning, zigzag, and stopping maneuvers of a subject ship were simulated to develop methods of ship barrier estimation, navigation safety-index, probability estimation of ships on collision courses upon taking crash astern maneuvers, and probability of collision in the bend of new canal.

3.2 The MMG Model

The three degree of freedom of ship motions including surging, swaying and yawing motions were implemented in this study. The coefficients of hull, rudder and propeller involved on the equations of the motions were adopted from the MMG model [24]. The coordinate system of the model is shown in Figure 3-1.

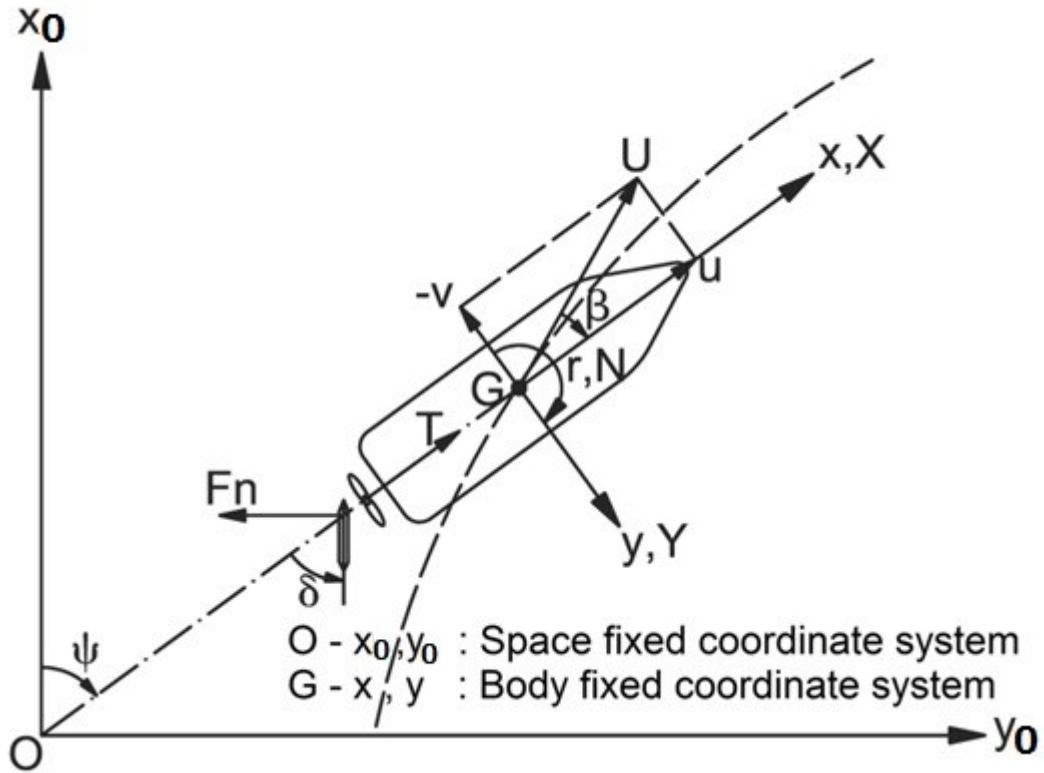


Figure 3-1 Coordinate system of MMG model

The model consists of three motions including surging, swaying, and yawing motions as expressed in Equation (3-1) to Equation (3-3). The rolling motion is not considered in this model. An approximation of the hull forces and hull moment is carried out based on polynomial expressed by Equation (3-4) to Equation (3-6). The variables of the polynomial equations are the drift angle, β and dimensionless turning rate, r' .

$$\text{Surge: } (m + m_x)\dot{u}_G - (m + m_y)v_G r_G = X_H + X_P + X_R + X_W \quad (3-1)$$

$$\text{Sway: } (m + m_y)\dot{v}_G + (m + m_x)u_G r_G = Y_H + Y_P + Y_R + Y_W \quad (3-2)$$

$$\text{Yaw: } (I_{zz} + J_{zz})\dot{r}_G = (N_H + N_P + N_R + N_W) - x_G(Y_H + Y_P + Y_R + Y_W) \quad (3-3)$$

$$X_H + m_y v_G r_G = 0.5 \rho L d U^2 \{X'_0 + X'_{\beta\beta} \beta^2 + (X'_{\beta r} - m'_y) \beta r' + (X'_{rr} - x'_G m'_y) r'^2 + X'_{\beta\beta\beta\beta} \beta^4\} \quad (3-4)$$

$$Y_H - m_x u_G r_G = 0.5 \rho L d U^2 \{Y'_\beta \beta + (Y'_r - m'_x) r' + Y'_{\beta\beta\beta} \beta^3 + Y'_{\beta\beta r} \beta^2 r' + Y'_{\beta rr} \beta r'^2 + Y'_{rrr} r'^3\} \quad (3-5)$$

$$N_H = 0.5 \rho L d U^2 \{N'_\beta \beta + N'_r r' + N'_{\beta\beta\beta} \beta^3 + N'_{\beta\beta r} \beta^2 r' + N'_{\beta rr} \beta r'^2 + N'_{rrr} r'^3\} \quad (3-6)$$

where:

$$r' = r(L/U)$$

$$x'_G = x_G / L$$

$$m'_x, m'_y = m_x, m_y / 0.5 \rho L^2 d$$

$$X'_0 = \text{dimensionless resistance} = X_0 / 0.5 \rho L d U^2$$

$$L = \text{ship length between perpendiculars (Lpp)}$$

$$U = \text{ship speed}$$

$$x_G = \text{longitudinal center of gravity}$$

$$m = \text{ship mass}$$

$$m_x = \text{longitudinal added mass}$$

$$m_y = \text{transversal added mass}$$

$$X_0 = \text{ship resistance}$$

$$\rho = \text{density of water}$$

$$d = \text{mean draught}$$

Kijima's equations for 4 linear hull derivatives, as expressed in Equation (3-7) to

Equation (3-10), and Yoshimura's equations for 11 nonlinear hull derivatives, as shown in Equation (3.11) to Equation (3-22), are taken from the model of the hull derivatives for medium high-speed merchant ships and fishing ships [24].

$$Y'_\beta = Y'_{\beta 0} (1 + 0.54\tau'^2) \quad (3-7)$$

$$Y'_r - m'_x = (Y'_r - m'_x)_0 (1 + 1.82\tau'^2) \quad (3-8)$$

$$N'_\beta = N'_{\beta 0} (1 - 0.85\tau'^2) \quad (3-9)$$

$$N'_r = N'_{r0} (1 + 0.33\tau'^2) \quad (3-10)$$

where: $\tau' = \text{trim}/d$

$$Y'_{\beta 0} = 0.5\pi k + 1.4C_b/(L/B)$$

$$(Y'_r - m'_x)_0 = 0.5C_b/(L/B)$$

$$N'_{\beta 0} = k$$

$$N'_{r0} = 0.54k + k^2$$

$$k = 2d/L$$

C_b = the block coefficient of the ship

trim = the different between the draft at fore perpendicular and after perpendicular

$$X'_{\beta\beta} = 1.15C_b/(L/B) - 0.18 \quad (3-11)$$

$$X'_{\beta r} - m'_y = -1.91C_b/(L/B) + 0.08 \quad (3-12)$$

$$X'_{rr} + x'_G m'_y = -0.085C_b/(L/B) + 0.008 \quad (3-13)$$

$$X'_{\beta\beta\beta} = -6.68C_b/(L/B) + 1.10 \quad (3-14)$$

$$Y'_{\beta\beta\beta} = 0.185L/B + 0.48 \quad (3-15)$$

$$Y'_{\beta\beta r} = 0.97\tau'/C_b - 0.75 \quad (3-16)$$

$$Y'_{\beta rr} = 0.26(1 - C_b)L/B + 0.11 \quad (3-17)$$

$$Y'_{rrr} = 0.069\tau' - 0.051 \quad (3-18)$$

$$N'_{\beta\beta\beta} = 0.69C_b + 0.66 \quad (3-19)$$

$$N'_{\beta\beta r} = 1.55C_b/(L/B) - 0.76 \quad (3-20)$$

$$N'_{\beta rr} = 0.075(1 - C_b)L/B - 0.098 \quad (3-21)$$

$$N'_{rrr} = 0.25C_b/(L/B) - 0.056 \quad (3-22)$$

The added mass in the x direction, m_x ; added mass in the y direction, m_y ; and added mass moment of inertia, J_{zz} , are calculated according to Motora's diagrams [25, 26, and 27]. The longitudinal added mass, transversal added mass, and added mass moment of inertia of subject ship selected in this study are as following.

$$m_x = 0.0098 \left(\frac{\rho}{2} \right) L^2 d \quad (3-23)$$

$$m_y = 0.1370 \left(\frac{\rho}{2} \right) L^2 d \quad (3-24)$$

$$J_{zz} = 0.00634 \left(\frac{\rho}{2} \right) L^4 d \quad (3-25)$$

The ship mass m , is calculated based on the density of the water in Tanjung Perak [28]. The density ρ , is 1.021 g/cm³. The moment of inertia of ship is calculated as follows:

$$I_{zz} = \left(\frac{1}{8} \right) \left(\frac{C_b}{L/B} \right) \left(\frac{\rho}{2} \right) L^4 d = \left(\frac{1}{16} \right) mL^2 \quad (3-26)$$

The forces and moment induced by the propeller are calculated according to Equation (3-27) to Equation (3-29).

$$X_P = (1 - t_P)\rho K_t D_P^4 n^2 \quad (3-27)$$

$$Y_P = 0 \quad (3-28)$$

$$N_P = 0 \quad (3-29)$$

where:

D_P = propeller diameter

n = propeller revolution (rps)

K_T = thrust coefficient

The trust coefficient of the subject ship is as follows:

$$K_T = 0.33 - 0.22J_P - 0.16J_P^2$$

$$J_P = U(1 - w_P)/(nD_P)$$

$1 - t_P$ = thrust deduction factor

$1 - w_P$ = effective wake fraction of propeller

$$t_P = 0.5C_p - 0.12$$

$$w_P = 0.7C_p - 0.18$$

C_p = the prismatic coefficient of the ship

The relation between trust coefficient and apparent advance constant for reversing propeller is adopted from K_T - J_S diagram for container ship [29, 30]. The trust coefficient for reversing propeller is presented in the fourth quadrant of Figure 3-2.

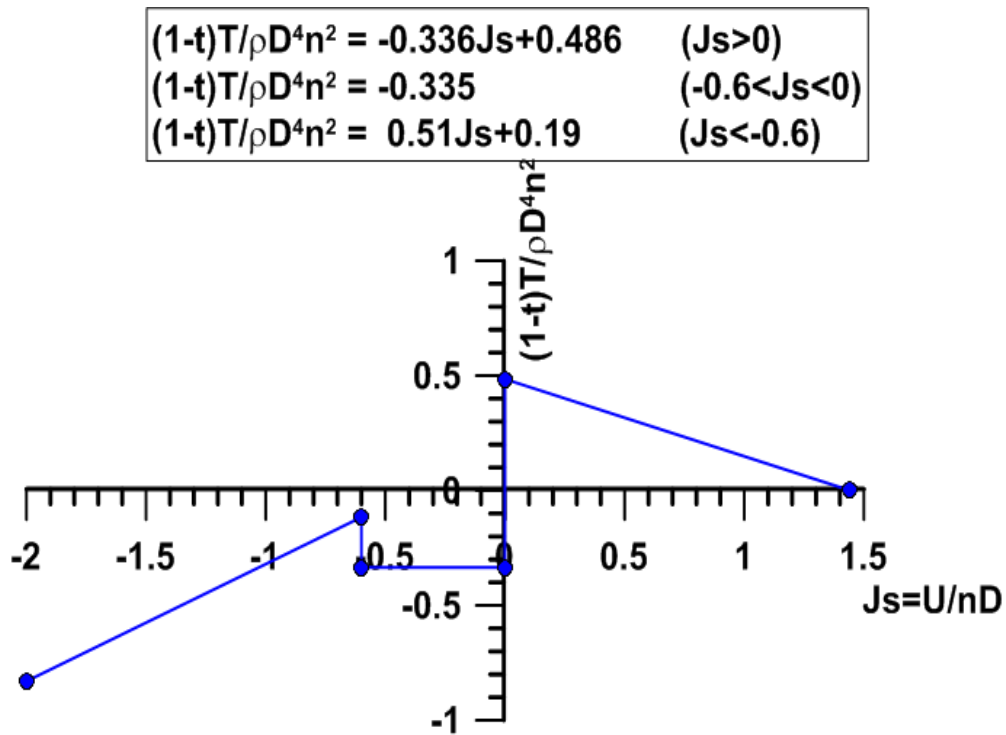


Figure 3-2 K_T - J_S diagram for container ship

Lateral force and yaw moment exerted by reversing propeller are taken from Yoshimura graphs [30] as shown by Figure 3-3.

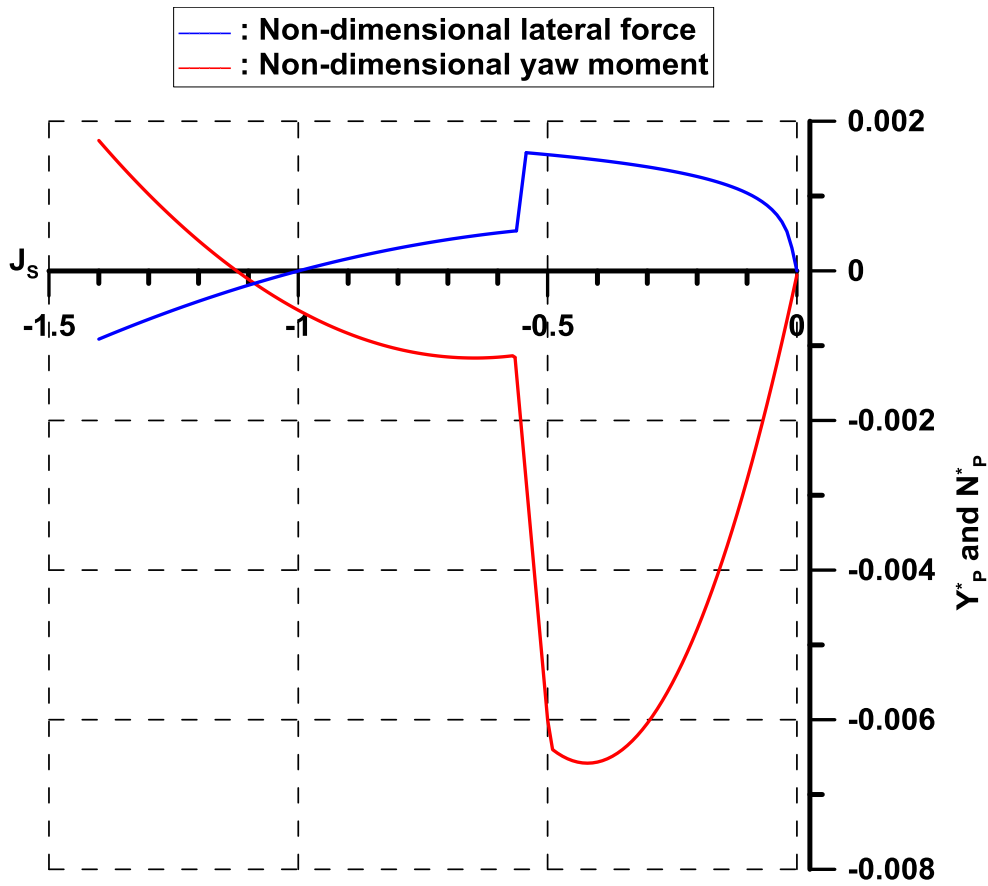


Figure 3-3 Lateral force and yaw moment exerted by reversing propeller

The graph is divided into three sections and each section fits to Equations (3-30) to (3-35) as below.

$$Y_p^* = 0.005125J_s^2 + 0.006629J_s + 0.000978 \quad \text{for: } J_s \leq -0.5653 \quad (3-30)$$

$$Y_p^* = -0.074153J_s - 0.043076 \quad \text{for: } -0.5653 < J_s \leq -0.5 \quad (3-31)$$

$$Y_p^* = 0.037007J_s^2 + 0.031084J_s - 0.000054 \quad \text{for: } -0.5 < J_s \leq 0 \quad (3-32)$$

$$N_p^* = -0.001255J_s^2 - 0.000734J_s + 0.000519 \quad \text{for: } J_s \leq -0.5625 \quad (3-33)$$

$$N_p^* = 0.049018J_s + 0.028116 \quad \text{for: } -0.5625 < J_s \leq -0.5429 \quad (3-34)$$

$$N_p^* = 0.000319 \ln(-J_s) + 0.001774 \quad \text{for: } -0.5429 < J_s \leq 0 \quad (3-35)$$

Y_p^* and N_p^* are typical non-dimensional form of lateral force and yaw moment exerted

by reversing propeller and the lateral force and yaw moment exerted by the reversing propeller are as following.

$$Y_P = Y_P^* \frac{\rho}{2} L d (nD)^2 \quad (3-36)$$

$$N_P = N_P^* \frac{\rho}{2} L^2 d (nD)^2 \quad (3-37)$$

The rudder forces and moment are calculated according to Equations (3-38) to (3-40).

$$X_R = -(1 - t_R)(0.5\rho L d U^2) F'_N \sin \delta \quad (3-38)$$

$$Y_R = -(1 - \alpha_H)(0.5\rho L d U^2) F'_N \sin \delta \quad (3-39)$$

$$N_R = -(x'_R + \alpha_H x'_H)(0.5\rho L d U^2) F'_N \sin \delta \quad (3-40)$$

where:

x'_R = dimensionless location of rudder from the midship relative to ship length

δ = rudder angle

t_R, α_H, x'_R = interaction coefficients

$$1 - t_R = 0.32\tau' + 0.61$$

$$\alpha_H = 3.6C_b/(L/B)$$

$$x'_H = -0.4$$

$$F'_N = (A_R/Ld) f_\alpha U_R'^2 \sin \alpha_R$$

A_R = movable area of rudder

$$f_\alpha = 6.13\lambda/(2.25 + \lambda)$$

λ = the aspect ratio of the rudder

$$U_R' = (u_R'^2 + v_R'^2)^{\frac{1}{2}}$$

$$\alpha_R = \delta - \tan^{-1}(-v_R'^2/u_R'^2)$$

$$u_R' = \varepsilon(1 - w_P)(\eta\{1 + \kappa((1 + 8K_T/\pi J_P)^{\frac{1}{2}} - 1)\}^2 + (1 - \eta))^{\frac{1}{2}}$$

$$v'_R = \gamma_R(v' - r'l'_R)$$

$$\eta = D_p/\text{rudder height}$$

$$l'_R = -0.9$$

$$\gamma_R = 2.06C_b/(L/B) + 0.14$$

$$\varepsilon = 2.26 - 1.82(1 - w_p)$$

$$k_x = \varepsilon K = 0.55$$

3.3 Subject Ship

A pure car carrier (PCC) ship is selected as the subject ship based on the maximum size of ship voyaging in the research area. In addition, the ship's main dimension of subject ship is appropriate to the requirement of the nonlinear hull derivatives for the MMG model, including the beam to length (L/B), beam to draught ratio (d/B) and block coefficient (Cb). The principle dimension of the subject ship is presented in Table 3-1.

Table 3-1 Principle dimension of PCC ship

Ship Particulars	Dimension
Length (Lpp)	180 m
Breadth (B)	32.2 m
Draft (d)	8.2 m
Coefficient Block (Cb)	0.548
Displacement (Δ)	26,650 tons
Speed (Vs)	18 kts
Propeller Diameter (Dp)	5.7 m
Ratio of Rudder Area to Vertical Longitudinal Section Area of Hull	0.0256

The requirements for the application of the derivatives for the MMG model are presented by Equations (3-41) to (3-44).

$$2.6 < L/B < 7.1 \quad (3-41)$$

$$0.25 < d/B < 0.46 \quad (3-42)$$

$$0.51 < C_b < 0.65 \quad (3-43)$$

$$0 < trim/d < 1.17 \quad (3-44)$$

3.4 Environment Effects

The wind and current disturbances, and the effect of shallow water condition are considered on the MMG model. The effects are described in the following sections.

3.4.1 Wind Effects

The effects of wind on ship maneuvering are calculated in the MMG model based on Fujiwara's [31] estimation of wind forces and moment, as expressed by Equations (3-45) to (3-47).

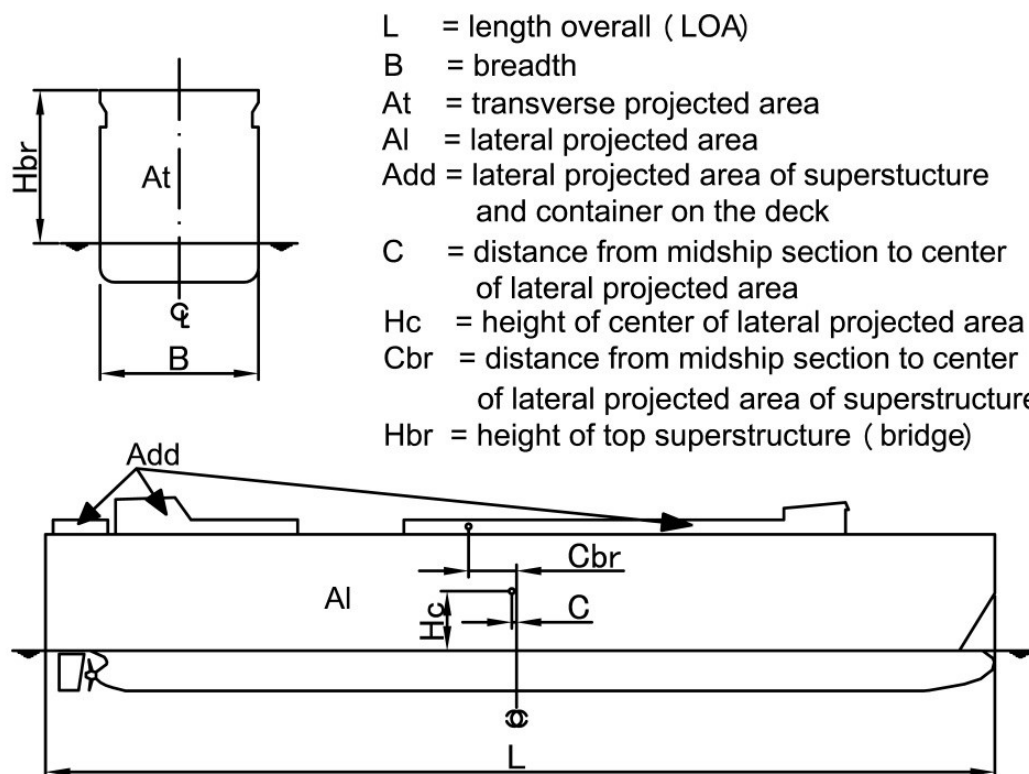


Figure 3-4 Wind force variables

$$X_w = \frac{1}{2} \rho_{air} U_w^2 A_T (X_0 + X_1 \cos \Psi + X_3 \cos 3\Psi + X_5 \cos 5\Psi) \quad (3-45)$$

$$Y_w = \frac{1}{2} \rho_{air} U_w^2 A_L (Y_1 \sin \Psi + Y_3 \sin 3\Psi + Y_5 \sin 5\Psi) \quad (3-46)$$

$$N_w = \frac{1}{2} \rho_{air} U_w^2 L A_L (N_1 \sin \Psi + N_2 \sin 2\Psi + N_3 \sin 3\Psi) \quad (3-47)$$

where:

ρ_{air} = the density of air

U_w = the velocity of wind

L = the LOA of the ship

Ψ = the angle of wind attack

A_T = the transverse projected area, and

A_L = the lateral projected area.

Other parameters are determined using regression equations [31] based on the variables shown in Figure 3-4.

3.4.2 Current Effects

The current effect is calculated based on the relative velocity with respect to the moving frame as shown in Figure 3-5. In this case, the variables of U , u_G , v_G , and r_G involved in Equations (3-4) to (3-6) are represented by the Equations (3-48) to (3-51) as following.

$$U = U_r = \sqrt{u_r^2 + v_r^2} \quad (3-48)$$

$$u_G = u_r = (u_b - u_c) = (u_b - U_c \cos \psi_{c_r}) \quad (3-49)$$

$$v_G = v_r = (v_b - v_c) = (v_b + U_c \sin \psi_{c_r}) \quad (3-50)$$

$$r_G = \dot{\psi}_{c_r} \quad (3-51)$$

where:

U_c = current speed

$\psi_{c_r} = \psi - \psi_c$

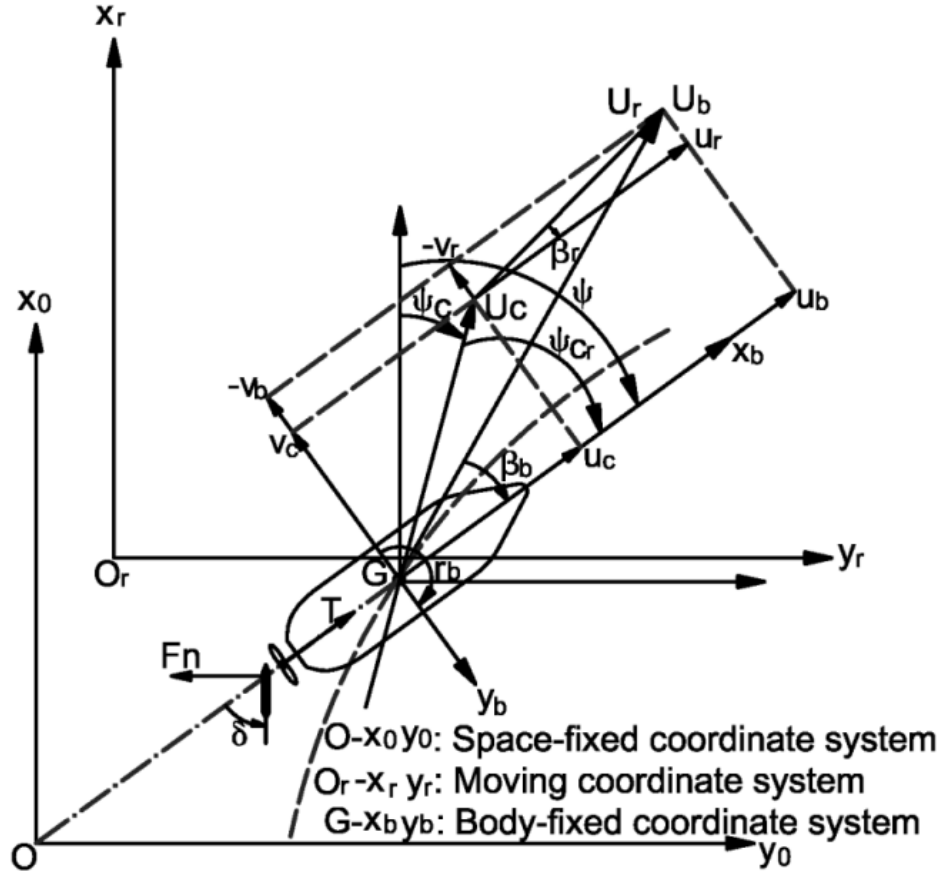


Figure 3-5 Moving frame method

3.4.3 Shallow Water Effects

The classification of shallow water is expressed by Vantorre [32] as $1.2 < d/H < 1.5$. Where d/H is the ratio between ship draught and water depth. The depth of the canal is 12 m, and the depth of the anchorage area is approximately 9 m. The MMG model considers the effects of shallow water according to Kobayashi equations [33] as following.

$$\frac{(Y'_v)_s}{(Y'_v)_d} = \frac{\frac{\pi}{2} \left(\frac{1}{\frac{1}{2} \frac{d}{H} (k + \pi \cot \frac{\pi d}{2H})} \right)^{q_1} + p C_b B/L}{\frac{\pi}{2} k + p C_b B/L} \quad (3-52)$$

$$\frac{(N'_v)_s}{(N'_v)_d}, \frac{(Y'_r)_s}{(Y'_r)_d}, \frac{(N'_r)_s}{(N'_r)_d}, etc. = \left(\frac{1}{\frac{1}{2} \frac{d}{H} (k + \pi \cot \frac{\pi d}{2H})} \right)^{q_2} \quad (3-53)$$

where:

$$q_1 = 3$$

$$q_2 = 1.4 \quad \text{for: } N'_v$$

$$q_2 = 1.2 \quad \text{for: } Y'_r$$

$$q_2 = 0.5 \quad \text{for: } N'_r$$

$$p = 1.4, \text{ as adopted from Yoshimura et al. [13].}$$

The added mass and the added mass moment of inertia are corrected as following.

$$\frac{(\text{Coefficient})_s}{(\text{Coefficient})_d} = 1 + q_3 \left\{ \tan \frac{\pi}{2} \left(\frac{d}{H} \right) \right\}^{q_4} \quad (3-54)$$

where:

$$q_3 = 0.21 \quad \text{for: } m' + m'_y$$

$$q_3 = 0.15 \quad \text{for: } I'_{zz} + J'_{zz}$$

$$q_4 = 1.2 \quad \text{for: } m' + m'_y \text{ and } I'_{zz} + J'_{zz}$$

The effect of shallow water on other coefficients, such as $f(v' + l'_R r')$, ε , and κ , is expressed by Equation (3-55).

$$\frac{(\text{Coefficient})_s}{(\text{Coefficient})_d} = 1 + q_5 \left(\frac{d}{H} \right)^{q_6} \quad (3-55)$$

where:

$$q_5 = 1.4 \quad \text{for: } f(v' + l'_R r')$$

$$q_5 = 0.8 \quad \text{for: } \varepsilon$$

$$q_5 = -1.2 \quad \text{for: } \kappa$$

$$q_6 = 3 \quad \text{for: } f(v' + l'_R r'), \varepsilon, \text{ and } \kappa$$

Chapter 4

Navigational Safety in New Port of Lamong Bay

4.1 Introduction

The Port of Lamong Bay shown in Figure 4-1 is a new port that is still under construction. It is located in the Madura Strait, Indonesia. The new port is intended to anticipate the increasing number of ship calls in the Port of Tanjung Perak. Ships enter the port by passing through a passage located between the position of the new port and an anchorage area. This is a danger area, where two container ships sank in the first quarter of 2014. Two ship-to-ship collisions have occurred, followed by the wayward ships sinking. A container ship, KM Tanto Hari, entered the port area at 09:45 on January 31, 2014. The ship could not be controlled due to the wind force, and attacked an anchored tanker, KM Serious, in the anchorage area. KM Tanto Hari sank within half an hour of the collision [34].

In a separate incident, the container ship KM Journey was moving from the anchorage area to the Port of Tanjung Perak around 02:20 on April 1, 2014. The ship drifted due to the current force, and attacked KM Lambelu in the anchorage area. KM Journey also sank after the collision [35]. The disturbances caused by wind and current contributed to incorrect maneuvers when entering and leaving the area. The restricted area makes the passage unsafe for navigation. Thus, it is crucial to analyze the safety of a ship leaving the new port. In this study, a scenario was simulated to allow a ship to avoid a collision with a target ship entering the area. This study has been published by the Journal of Marine Engineering Frontier [36]

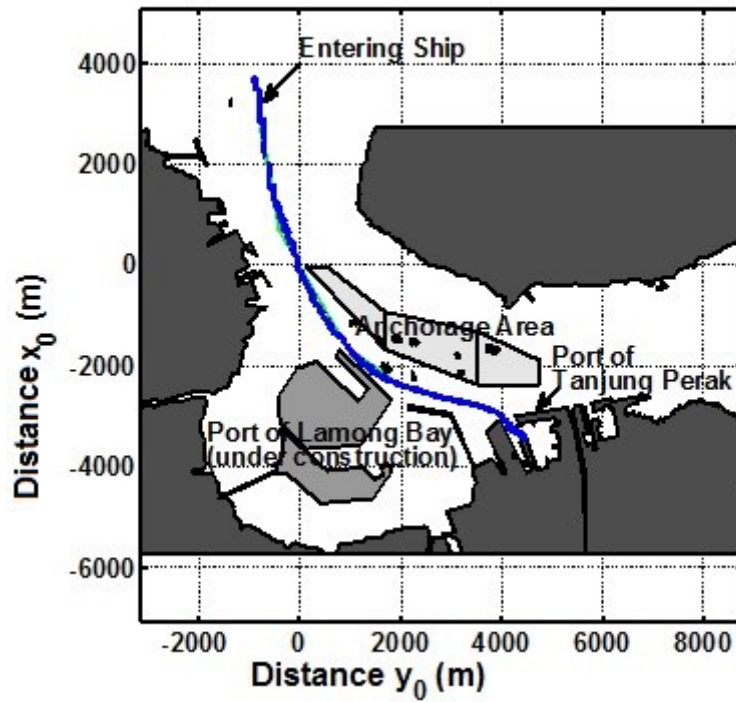


Figure 4-1 Area of Lamong Bay Port

The Madura Strait, which is located between Java and the Madura Islands, is one of the important fairways in Indonesia. Tanjung Perak Port, which is located in the strait, plays an important role in domestic and international trade. A map of the new port used in this study was introduced in another paper about PAW [37]. The passage between the new port and anchorage zones is one of the danger areas in the port area, as shown in another paper about trial maneuvers [38]. Figure 4-1 shows the positions of the Lamong Bay Port and a target ship entering the Tanjung Perak Port. The objective of this paper is to identify a danger area for a ship in the new port area and propose scenarios for collision avoidance when leaving the new port of Lamong Bay. This paper proposes a method of collision avoidance by estimating the width of ship domain in port area based on the concept of PAW.

4.2 Literature Review

The ship domain concept and the indices of the distance to the closest point of approach (DCPA) and the time to reach the point (TCPA) have been widely used in collision risk assessment and collision avoidance systems. A quantitative assessment of marine traffic

safety using the minimum distance to a collision has been developed on the basis of the position, course, speed, and maneuverability of ships [17]. The DCPA and TCPA indices have been implemented in the intelligent collision avoidance system of a ship handling simulator [39]. Wang et al. [40] proposed a mathematical description for each type of ship domain. Szlapczynski [41] introduced the approach factor, f , as a new measure of collision risk, which considers the courses of both ships and can be used for any type of ship domain.

However, the ship domain in a restricted area such as a port has not been widely investigated. The minimum distance between ships in a harbor, as well as the minimum distance to other obstacles such as the port structure and anchored ships, was proposed by Inoue [42].

This paper introduces a new obstacle that represents the danger area of a port produced by a target ship during maneuvering. The danger area of a target ship entering a port area is simulated based on the concept of potential area of water (PAW) for maneuvering. The width of the space between the port structure and the danger area is identified. The safest route for a ship to avoid the danger area and other obstacles is simulated by considering a navigation safety index.

Inoue and Usui [43] used an environmental stress (ES) model to systematically analyze the difficulty of maneuvering a ship between anchored ships, where the arrangement of the anchorages was designed according to the allowable level of difficulty for mariners. The emergency level (EL), another index to estimate the potential risk of a maritime accident was introduced by Yasuda et al. [44].

Zhuo et al. [45] used maneuvering simulation for trial maneuvers to develop a ship-based intelligent anti-collision decision-making support system. This system assumed that an automatic identification system (AIS) was installed onboard, and an offline adaptive neuro-fuzzy inference system was used to determine the time required to take action to avoid a collision with another ship. The time to take action and angle between the original and new courses were determined.

This paper introduces a collision avoidance method based on the uncertainty of a target ship's path presented by the PAW for maneuvering. The time series for the rudder angle and propeller revolutions of the subject ship leaving the new port are determined for the

safest route by considering the probable path of the target ship in the PAW. The navigational safety of ship leaving the port is analyzed using the EL method.

4.3 Data

4.3.1 AIS Data

The AIS data were obtained from an AIS receiver installed at the Institut Teknologi Sepuluh Nopember, Indonesia. The installation was performed with the cooperation of Kobe University, Japan. In this study, the data is taken from a 15 minutes trajectory of an entering ship in the research area. The data has been presented in Section 2.3.1.

4.3.2 Environmental Data

The environmental data for the wind and current in the port area used in the simulation are taken from the data distributions in January 2009 and January 2010. The data were obtained from the maritime climatology station in Tanjung Perak.

The distribution of the wind speed fits a Weibull distribution with the following parameters: α is 2.053 and β is 1.744. Where, $\beta > 0$ is the shape parameter, and $\alpha > 0$ is the scale parameter. The cumulative density of a wind with a rating of one on the Beaufort wind scale, which represents a typical wind speed of 1–3 kts or around 0.5–1.5 m/s, is about 42%. The shape parameter β is more than 1 means that the probability density function of wind speed tends to increase by the wind speed from 0.5 to 1.5 m/s. This is categorized as a light wind by the World Meteorological Organization (WMO). In the rainy season (October–April), the wind direction is west (W), which means the wind blows from the west to the east. The cumulative density of the wind between 247.5° (WSW) and 292.5° (WNW) is about 45%. Based on the distributions, the most probable wind speed and wind direction in the port area in January are 1.25 m/s and 260° with probabilities of 14.5% and 13.5%, respectively.

The distribution of the current speed fits a Weibull distribution with an α of 1.284 and β of 0.045. The density of a current speed of less than 0.1 m/s is about 94%. The shape parameter β is less than 1 means that the probability density function of current speed tends to decrease by the current speed from 0 to 0.1 m/s. The current direction also indicates the direction from which the current originates. The directions between 90° (E) and 112.5° (SEE)

have a cumulative density of about 85%. The most probable current speed and current direction are 0.0125 m/s and 98° with probabilities of 19% and 23.5%, respectively. The depth of the water in the area is about 9.5 m.

4.4 Methods

A simulation is conducted using the MMG model, which considers the effects of shallow water and wind and current disturbances. The MMG model has been described in Chapter 3. The method to estimate the width of ship barrier is developed based on the concept of PAW. The PAW for maneuvering is defined as the water area that would be used by a ship before it completes its movement in cases where the navigator encounters an emergency [7]. The PAW was originally identified by superimposing the ship paths predicted by a ship navigating simulator. These ship paths were estimated from variations in the times to start a crash astern maneuver. In this paper, the PAW is determined not only by an emergency action but also by the uncertainty in ship maneuverability caused by the variation in the initial conditions. The PAW of a target ship is predicted on the basis of the distribution of the initial conditions derived from AIS data. The maneuvers of subject ship are simulated to avoid a collision with a target ship by considering the probable paths in the predicted PAW. The maneuvering safety is measured on the basis of the emergency levels (ELs).

The MMG model was developed in the MATLAB program by considering the effects of shallow water, wind, and current. An algorithm was developed for the maneuvering simulation, which randomized the initial ship conditions on the basis of the distribution derived from the AIS data, including the yaw rate, drift angle, and rudder angle. The algorithm was introduced in another paper about the uncertainty of ship maneuverability [46]. The distributions of the conditions were analyzed from AIS data for the Madura Strait and have been presented in Table 2-2. The rudder angle of the target ship entering the port area is predicted using a linear maneuvering model. The method used in this prediction is based on an attempt to predict the maneuvering indices with AIS [20] using the linear model. The K' and T' correlations [21] are implemented for the prediction.

The PAW-based method to determine the initial position, heading angle, rudder angle, and speed of a ship leaving the port of Lamong Bay in order to avoid a collision in the danger area posed by a target ship entering the port of Tanjung Perak is presented in Figure 4-2. The

AIS data provide data for target ships, including their positions, headings, and courses. The initial conditions of a target ship in the starting position of a maneuver are estimated based on the AIS data. The proposed method using AIS data analysis is shown by Figure 4-3. Other data for the target ships, including the hull, rudder, and propeller, are needed to simulate the PAW. Topography data for the port area and disturbances, including shallow water, wind, and current, are also included in the database for the ship dynamics and safety index calculations. The path of the subject ship to avoid a collision in the danger area of the PAW posed by the target ship is determined by simulating the trial maneuver.

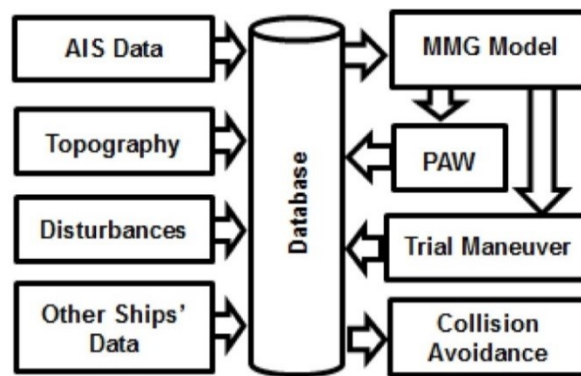


Figure 4-2 PAW-based collision avoidance

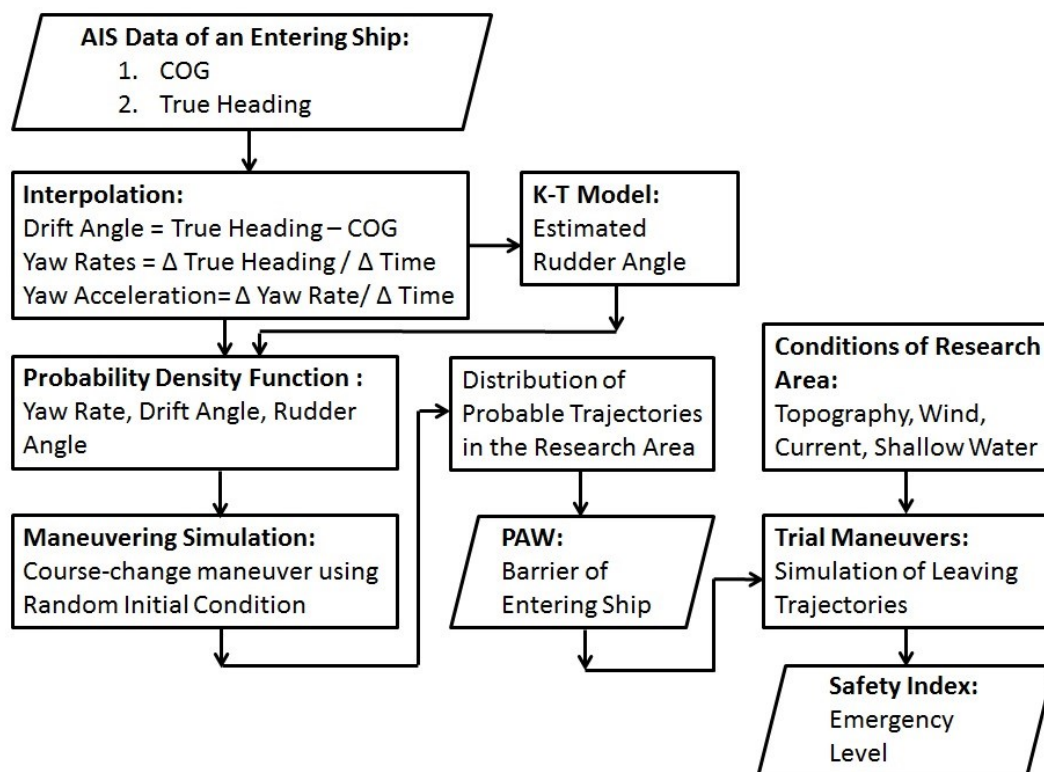


Figure 4-3 Proposed method

4.5 Results

The result of rudder estimation obtained by using the method are shown as a normal distribution of the rudder angle, with a mean of -0.11° and a standard deviation of 0.33° . The distributions of the yaw rate and drift angle are calculated based on the interpolation of the COG and ship heading presented in Table 2-1. The drift angle β is the difference between the heading and COG, as shown in Figure 3-1. The yaw rate is calculated from the differential of the ship heading. The distributions of the rudder angle, yaw rate, and drift angle of the target ship are presented in Table 2-2.

The target ship is simulated to enter the Port of Tanjung Perak by passing through the passage located between the anchorage zone and the Port of Lamong Bay, as shown by Figure 4-4. The figure shows the trajectory of the ship in blue, and the center of the passage in green. The PAW of the target ship is identified when it alters course at the bend of the passage. The simulation is treated by randomizing the initial conditions of rudder angle and yaw rate, with the mean of the drift angle. The form of the PAW is presented in Figure 4-5, which shows that the target ship enters the zone of the anchorage area. The figure confirms that this anchorage area is a danger area in this port. Both of the accidents in the first quarter of 2014 occurred in this area.

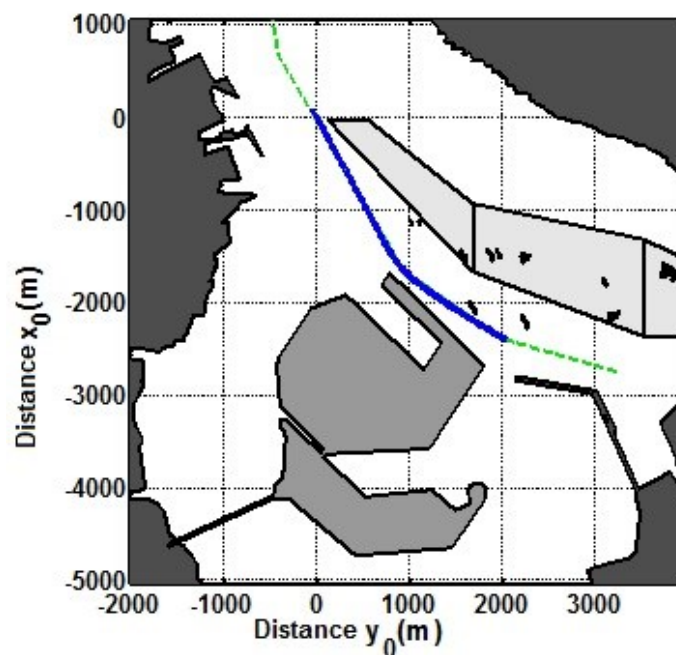


Figure 4-4 Passage between Port of Lamong Bay and anchorage zone

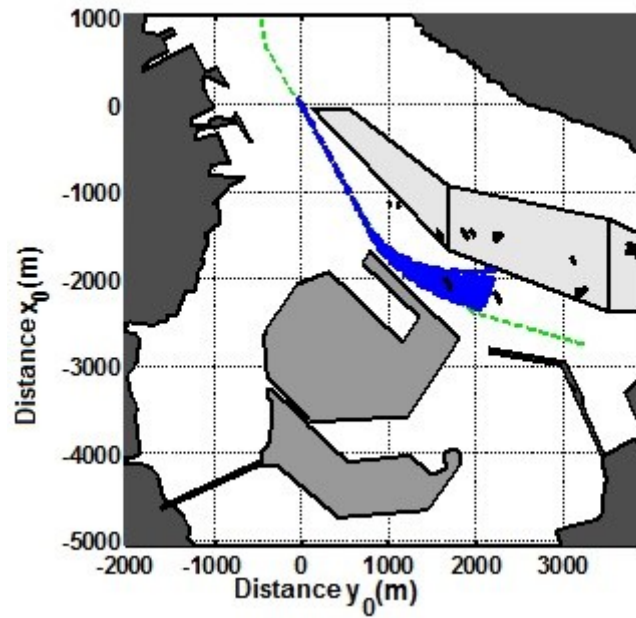


Figure 4-5 PAW for course alteration maneuver

In order to avoid collisions with the anchored ships in the area, the entering ship needs to take emergency action by utilizing a side thruster to keep the initial drift angle stable at 0.02 rad. A simulation of this emergency action using a constant drift angle during the maneuvering of the course alteration and the random initial values for the rudder angle and yaw rate is shown by the PAW in Figure 4-6.

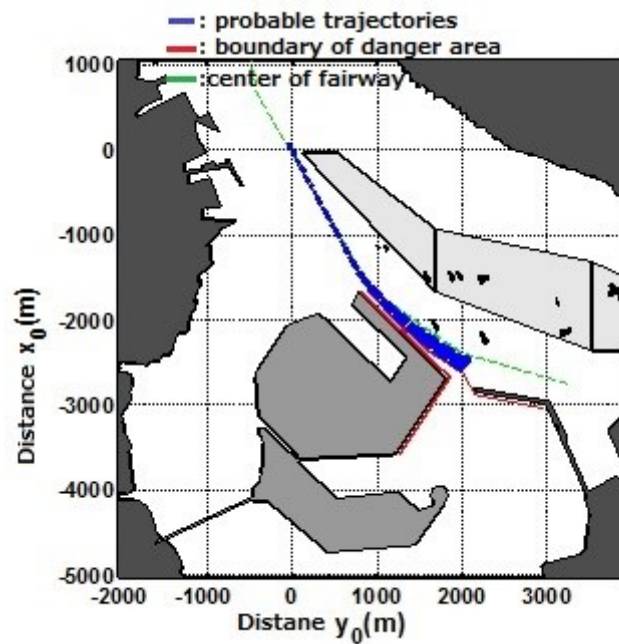


Figure 4-6 Danger area between Port of Lamong Bay and anchorage zone

The figure shows that the target ship is prevented from colliding with anchored ships. However, it creates a danger area for the subject ship leaving the Port of Lamong Bay. The maximum width of this danger area is $1.12L_t$, where L_t is the length of the target ship. The width of the danger area is less than the semi-minor of Fujii' ship domain [5], $1.6L$. The corresponding width introduced by Inoue [6] is $1.05L$, calculated from $0.5(0.008L_t + 0.667)L_o$, where L_o is the length of the subject ship, and L_t is the length of the target ship. In this simulation, L_t and L_o are the same, 180 m.

Figure 4-6 also shows the boundary of danger area for outgoing ship in red, the center of fairway in green, and the probable trajectories of incoming ship in blue. Area of the probable trajectories is defined as the new danger area. The minimum width of the space between the port structure and the danger area is only $0.56L$. This space is less than the minimum distance of a ship to a wharf proposed by Inoue, $0.68L$. This means that the space is very dangerous for a subject ship leaving the new port.

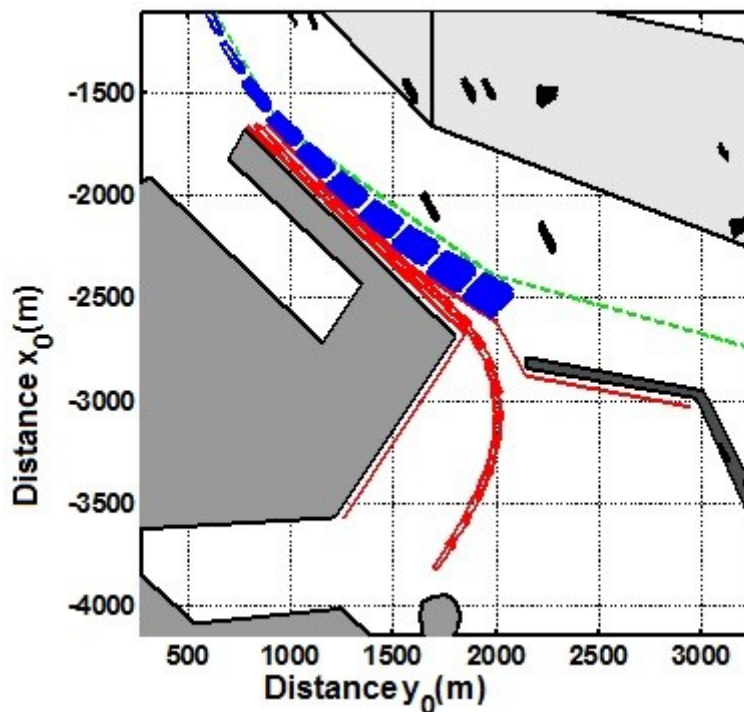


Figure 4-7 Trajectory of scenario 1

In this simulation, the subject ship leaving the Port of Lamong Bay is assumed to have the same main dimensions as the target ship. Two scenarios are considered in the simulation. First, the subject ship passes through the space between the danger area and port. Second, the

subject ship enters the passage at a position between the Port of Lamong Bay and the Port of Tanjung Perak and passes through the passage between the danger area and anchorage zone. The trajectory of the subject ship in the first scenario is shown by Figure 4-7. This trajectory is determined by considering the radius of turning (TR) of the subject ship, as shown by Figure 4-8.

The turning radius of the subject ship at a speed of 4.5 kn and rudder angle of 35° is about $3.25L_o$. The ship should take a parallel position with a distance of about $3.25L_o$ away from the port before making a turning maneuver. The time series of the rudder angle treated for the simulation is shown in Figure 4-9.

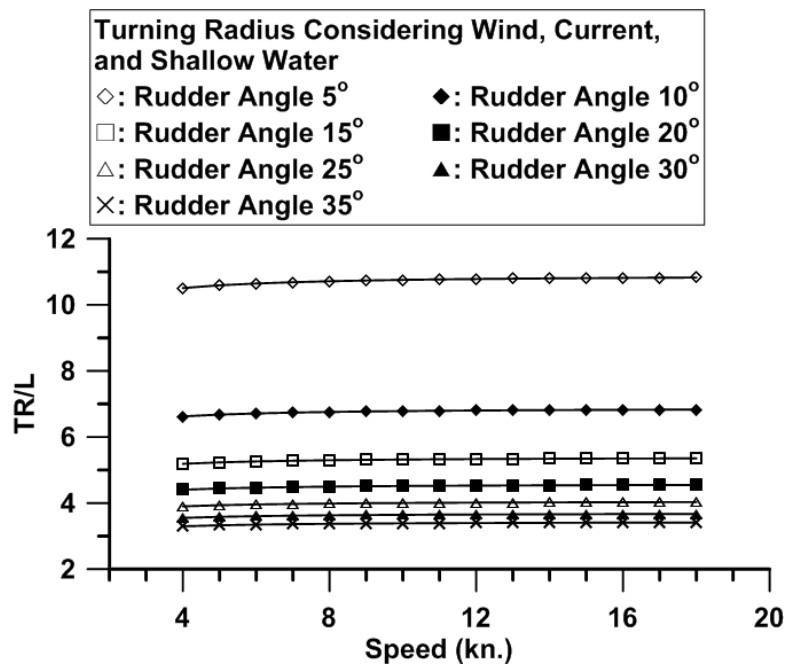


Figure 4-8 Turning radius by speed and rudder angle

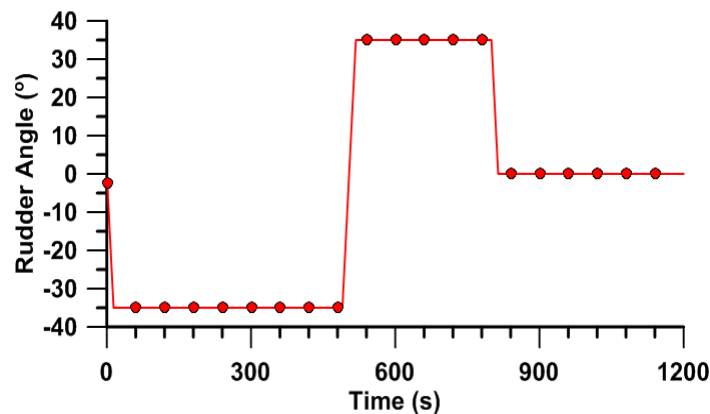


Figure 4-9 Time series of rudder angle

The safety index of the ship leaving the port is measured using the EL method. The implementation of this method in the simulation is based on the distance to the obstacle and the stopping distance. The obstacles are represented by red lines in Figure 4-6, and the stopping distance is calculated using the IMO estimation equation (2002). The EL of the ship is shown in Figure 4-10. This figure shows that the critical time for the ship occurs before entering the space between the port and danger area. This period is shown by first 600 s of the simulation in Figure 4-10, which represents the first 10 ships in Figure 5-7. In this period, the EL is generally positive. The EL is negative when the ship enters the space.

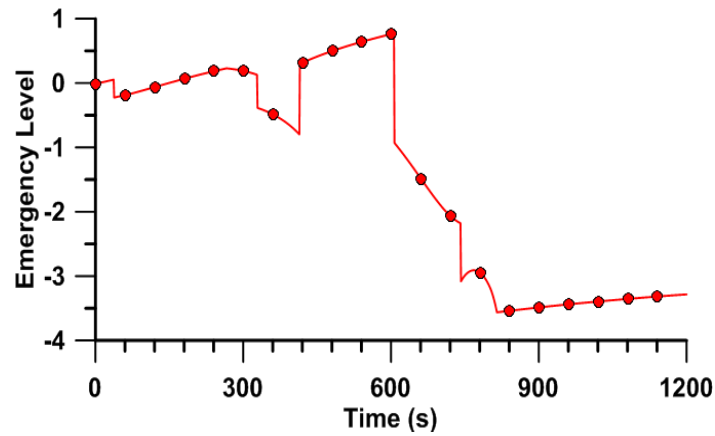


Figure 4-10 Emergency level time series of subject ship

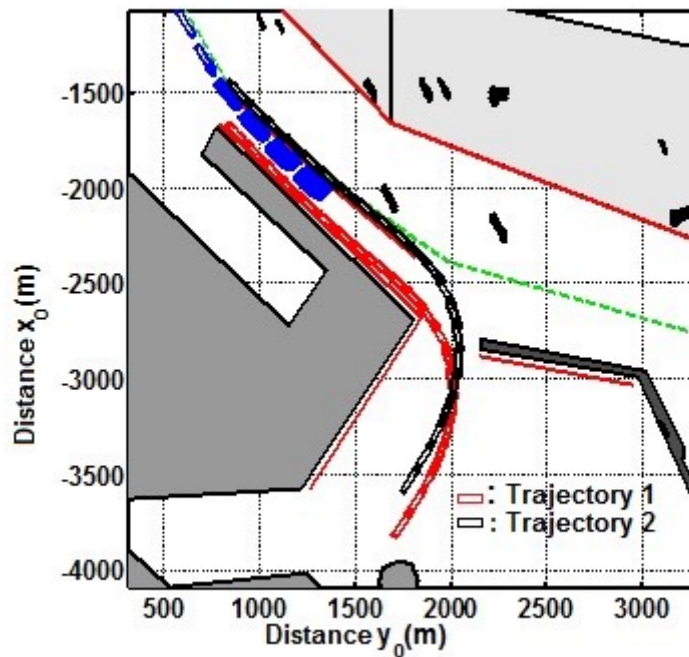


Figure 4-11 Trajectory of scenario 2

The trajectory of the second scenario is shown in Figure 4-11 in black. The subject ship should cross the danger area and enter the passage before the position of the target ship is around the middle of the port, which represents the semi-major of Fujii' ship domain, $4L$. This path is shown by the black trajectory. The minimum longitudinal distance between the ship and an anchored ship proposed by Inoue is $0.89L_0$.

Figure 4-11 shows that a ship is anchored too close to the passage, at about $0.5L_0$. Two ships are anchored outside the border lines for the anchorage area, as shown by the grey area in Figure 4-11. The border lines for the anchorage area are treated as obstacle lines in the calculation of the emergency level for trajectory 2. A comparison of the emergency levels for trajectories 1 and 2 is presented in Figure 4-12.

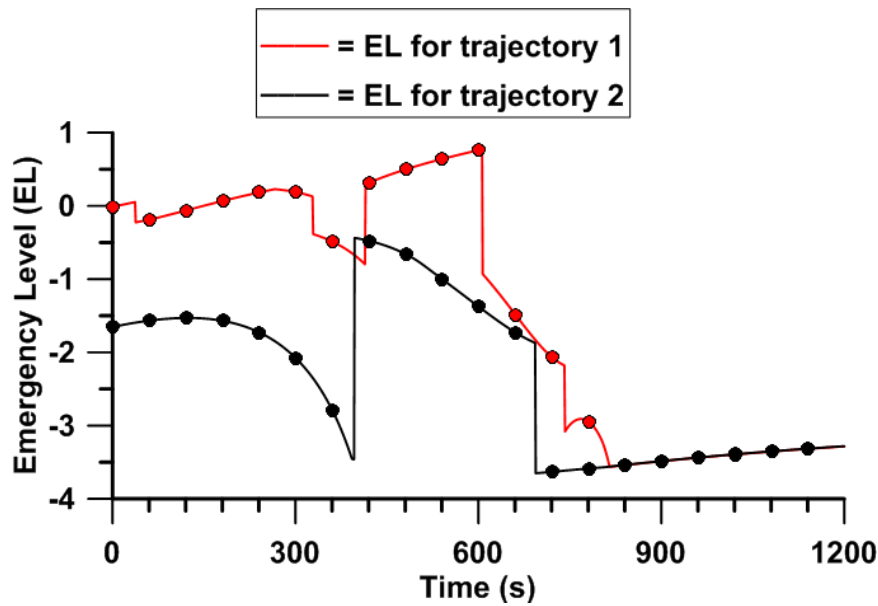


Figure 4-12 Comparison of EL

4.6 Discussions

The danger area produced by a target ship is identified. The distance of the danger area to the structure of the new port is less than the distance proposed by Inoue. However, the distance of the center of the passage to the border line of the anchorage zone is more than the required distance.

Based on the plot of the AIS data, two ships are anchored out of the anchoring zones and are very close to the center of the passage. Two scenarios involving a subject ship

leaving the new port and avoiding collision with a target ship in the danger area have been simulated. Accordingly, I propose suggestions to the port authority as following.

1. The position of the center of the passage is suggested to be moved about $0.5L$ or 90 m away from the position of the new port.
2. All ships should be anchored inside the anchoring area.
3. The first scenario is not suggested for a subject ship to leave the port. The path of the first scenario is only recommended in the case that the ship takes a berth near the danger area.
4. The second scenario is recommended for a subject ship to leave the new port.

4.7 Conclusions

The existing MMG model is refined in MATLAB, and the effects of shallow water and external disturbances are considered. A danger area consisting of the PAW for a target ship is identified on the basis of the probability distribution functions of the initial conditions, which are analyzed and predicted based on the AIS data.

The width of the danger area represented the width of ship domain. The width of the danger area, $1.12L$, was less than the semi-minor of Fujii' ship domain [5], $1.6L$, but it was almost the same as the minimum distance between ships in a harbor introduced by Inoue [6]. An anchored ship was identified at a position of less than $0.89L$, as proposed by Inoue.

In order to avoid a collision with a ship entering the danger area, two scenarios for a subject ship leaving the Port of Lamong Bay are simulated. The second scenario is safer than the first one, according to the index of emergency levels.

Based on the minimum distance criterion, these scenarios had almost the same difficulty. The width of the free space between the danger area and port structure in the first scenario was $0.56L$, and the distance between the passage and an anchored ship in the second scenario was only $0.5L$. For these scenarios, the corresponding minimum distances proposed by Inoue were $0.68L$ and $0.89L$. Accordingly, I proposed that the center of the passage should be changed, and all the ships should be anchored inside of the anchorage zone. The second scenario was suggested for the subject ship based on the emergency level criterion.

The propeller revolutions, rudder angles, and initial heading of the subject ship leaving the new port area were determined, and the emergency level of the ship was calculated. Both of the scenarios showed the need for future work involving other emergency actions such as crash astern maneuvers to identify the other danger areas in the Madura Strait based on simulations using the MMG model and AIS data.

Chapter 5

Development of Navigation Safety-Index Methods

5.1 Introduction

The evaluation of ship routes in a developing port area is essential to optimize the safety index of ships navigating in the area. Researchers have introduced several navigation safety-index methods. However, none of the methods is intended to address the specific goal of seeking the safest route. The danger score (DS), a comprehensive method considering several sub-factors weighted based on the perception of navigators, is used for evaluating the danger of a route [16]. Environment stress (ES) is used for evaluating the stress level in the port area faced by navigators and is based on subjective judgment by simulating 180 courses between -90° and $+90^{\circ}$ [47]. The minimum distance to collision (MDTC) is the minimum distance between two ships determined by the ships' courses, speed, and maneuverability to avoid collision [17]. Unsafe ship handling (US) and emergency level (EL) represent the safety level of a ship on a specific course in an area based on the time to collision and shortest stopping time of the ship [44, 48]. The US and EL methods are able to determine the safest route by evaluating all of the paths. However, a trial and error method is required to achieve this objective. This study proposes a method to seek the optimal safety index route using random initial conditions based on the distributions analyzed from the AIS data. For the case study, the method is implemented in the developing port area of Tanjung Perak Port, in the Madura Strait, Indonesia.

Recently, there have been an alarming number of ship accidents in Indonesia. Based

on data released by the national commission of transport accidents, there were 691 accidents between 2003 and 2008. Up to 37% of these accidents resulted in a sinking, 13% in a foundering, 15% in a collision, 18% in a fire, and 17% in other types of incidents. These accidents were attributed to human error (37%), technical error (23%), natural conditions (38%), and other causes (2%). Accident data for the Madura Strait, which includes the Tanjung Perak port area, confirms that 37.15% of the accidents during 2005–2010 were collisions [49].

In the first quarter of 2014, there were two ship-to-ship collisions in the Tanjung Perak port area located in the Madura Strait. In January 31, 2014, a container ship, KM Tanto Hari, sank after a collision with a tanker ship in the anchorage area. The ship executed an incorrect turning maneuver while entering the port area. Another container ship, KM Journey, sank following an encounter with a ferry on the night of March 31, 2014. The ship was also executing an improper maneuver while leaving the anchorage area. The effect of strong wind and current disturbances, congested traffic, and the lack of navigational aids in the research area were considered the causes of the accidents. In this paper, the effect of environmental disturbances is presented as the distribution of drift angle and yaw rate of the ships at their initial position of maneuvering upon entering the port through the passage between the anchorage zones. The distribution is analyzed using Automatic Identification System (AIS) data. The hypothetical optimal route is one of the recommendations for determining navigational aids such as the position of additional buoys. The passage enclosed by the anchorage zones is presented in Figure 2-2. This is the danger area where accidents can occur because of disturbances of wind and current in an uncontrolled environment.

The assessment of navigational safety and investigation of safety variables for accident prevention is mandatory in the Madura Strait because the number of ship accidents has reached an alarming level. Several methods have been proposed by researchers. Two of the available methods, EL [48] and ES [47], are implemented in this paper and based on these methods, a new method is proposed considering the distribution of the initial conditions in the research area. The uncertainty of a ship's trajectory is significantly influenced by the initial conditions of ship maneuvering including the surging and swaying speed and yaw rate, as presented in another paper [46]. In this paper, a method for the assessment of navigational safety considering the initial conditions of ship maneuvering is proposed. For the case study, the method is implemented on the passage located between anchorage zones of the port area in the Madura Strait.

The aim of this study is to implement the benefits of the available navigation safety assessment methods and to develop a new method considering course probability, based on the distribution of the initial conditions, of a turning maneuver in the passage located between the anchorage zones in the Madura Strait. A map of the passage between the five anchorage zones in the Madura Strait port is illustrated by the path of an entering ship in Figure 2-2. The path of the entering ship plotted in the figure is derived from AIS data.

The proposed method is developed based on the EL and ES methods introduced by other researchers [47, 48]. The new method considers the probability of ship courses based on the distribution of the yaw rate of the ships in the area. The proposed method addresses the following issues:

1. The scenario where the yaw rate is changed suddenly at the initial position of a ship maneuvering in the passage located between the anchorage zones is considered.
2. The distribution of ship courses based on the distribution of the initial condition is considered in the development of the navigation safety assessment method.
3. The initial drift angle is derived from the AIS data of the ships belonging to the same class. However, the distribution of the initial yaw rate at the initial position of the passage is analyzed using the simulation of a small zigzag maneuver. The trend of the yaw angle in the simulation is compared to the AIS data. This method is implemented because the yawing rate is not available in the AIS data.
4. The possible paths based on the distribution are estimated using the Maneuvering Modeling Group (MMG) model [23].
5. The new method is developed based on the concept of EL and ES. The optimal route is determined according to the proposed navigation safety index.

The EL and ES methods are selected because they require fewer factors than the DS method and the MDTC is only appropriate for implementation when the other obstacle is a moving vessel. In this paper, a new method is proposed to determine the safest route in the research area by considering the position of virtual obstacle lines. The new method is developed considering the probability of ship courses based on the distribution of the yaw rate of the ships at the initial position of the ship maneuvering in the research area, between the anchorage zones. The ship courses are estimated using the MMG model considering the effect of the wind, current disturbance, and effect of shallow water. The new navigational safety method is developed based on the concept of the shortest obstacle employed in the EL

method and the safest route is determined based on the concept of aggregate safety index discussed in the ES method.

5.2 Literature Review

The proposed method is initiated from the study of other navigation safety assessment methods. The summary of these methods is presented in the following.

DS is a navigation safety assessment method that considers five primary factors including ship conditions, human, environment, machinery, and navigational factors [16]. The method represents the safety index of vessels with a comprehensive calculation considering the main factors involved in traffic conditions. The factors are represented by multiple sub-factors requiring a consistency analysis to estimate the weight of the factors. The subjective responses to questionnaires for the estimation of the factors' weight present a difficulty for the implementation of this method.

Another method, the MDTC, which is simulated based on the position, course, speed, and maneuvering ability of ships, is used to develop a quantitative assessment of marine traffic safety [17]. The MDTC is defined as the minimum distance between two ships where a maneuver should be executed to avoid a collision. The effect of external disturbances and the possibility of a crash astern are not considered in the simulation. The method is used for developing the estimation of the number of ship-ship collision candidates [50].

The unsafe ship handling (US) and Emergency Level (EL) methods were introduced to estimate the safety index of a vessel by considering the conditions of the vessel and its environment. Human and navigational factors are not included in the estimation of both safety indices. The US and EL evaluate the ship's course in a trajectory considering the conditions of the ship and environment by estimating the navigational safety index. The indices are calculated based on the parameters of the Shortest Stopping Time (SST) and Time to Collision (TTC) depending on the vessel's maneuverability and distance to obstacles. The vessel is in an unsafe ship handling situation if the TTC is less than the SST [44]. The vessel is in a safe situation if the EL is negative [48]. Similar to the MDTC method, this method is a quantitative assessment method without consideration of the human and management factors.

An issue in the implementation of the EL method is the difficulty of estimating the stopping time in the presence of a crash astern action. A method for the estimation of the lateral forces and yaw moment for any type of ship reversing the propeller have not been widely investigated. The crash astern action is also not considered in the simulation of the MDTC method [17].

A safety evaluation of the traffic in ports and waterways using the Environment Stress (ES) index proposed by Inoue is a quantitative model that considers environmental conditions including topographical conditions, traffic congestion, and external disturbances. The index is also calculated based on the parameter of TTC and the conversion of this parameter into a subjective judgment (SJ) by a regression equation developed based on the questionnaire responses from navigators [47]. Variables for the ship length, ship capacity, speed, distance to obstacles, and types of collisions including head on, overtaking, and crossing from both the port and starboard are involved in the equations.

ES is used for the assessment of navigator difficulties for steering ship movement in a port area [47]. The method considers the ship-human-environment factors and uses a questionnaire to obtain the navigators' perception on multiple situations of ship courses within 180° in the restricted area. The subjective judgment of the navigators is formulated in a regression equation for the estimation of the ES.

5.3 AIS Data

In this study, the data is taken from 25 entering ships belonging to class C at the position of the research area. The data has been presented in Section 2.3.2.

5.4 Methods

5.4.1 Introduction to EL and ES Methods

The method proposed in this paper is developed based on the EL and ES methods. The EL and ES methods are also implemented individually in the research area and the results are compared to those of the proposed method. The methods are described as following.

The EL method is presented by Equation (5-11) as follows [48]:

$$EL(t) = 1 - SST/TTC(t) \quad (5-1)$$

where:

t = the time in s

SST = the Shortest Stopping Time

TTC = the Time to Collision.

In this study, for the implementation of the method in the research area, the SST does not reflect the crash astern situation. The SST is calculated by considering the stopping distance and ship speed. The stopping distance is estimated based on the International Maritime Organization (IMO) Maneuvering Explanatory Notes [51] and depends on the ship type, machinery type, and ship length. The time to collision, TTC, is calculated based on the distance to the closest obstacle and ship speed.

The ES method is implemented by simulating the ship courses between -90° and 90° from the current ship course along the ship's path. Subjective judgments based on topographical obstacles (SJ_L) and traffic obstacles (SJ_S) are made according to the equations proposed by Inoue et al. [47]. The ES is calculated based on Equations (5-2) and (5-3), [47].

$$SJ_L = \alpha(R/V) + \beta \quad (5-2)$$

where:

$$\alpha = -0.00092 \log_{10}(GT) + 0.0099, \text{ for } GT \leq 10,000 \text{ GT},$$

$$\alpha = 0.006671 \exp(-7 \times 10^{-6}(GT)), \text{ for } GT > 10,000 \text{ GT},$$

$$\beta = -3.82, \text{ GT is the gross tonnage of the ship,}$$

R is the distance to a topographical obstacle, and

V is the ship speed.

$$SJ_S = \alpha(R/L_m) + \beta \quad (5-3)$$

where:

$$\alpha = 0.0019.Lm,$$

$$\text{for ships from star board : } \beta = -0.65 \ln(Lm) - 2.07,$$

$$\text{for ships from port side : } \beta = -0.65 \ln(Lm) - 2.35,$$

$$\text{for head on condition : } \beta = -0.65 \ln(Lm) - 2.07,$$

$$\text{for overtaking condition : } \beta = -0.65 \ln(Lm) - 0.85,$$

Lm is the average length between the subject ship and a target ship, and

R is distance between the ships.

The course over ground (COG) is simulated to change between -90° and 90° from the COG calculated using the MMG model. The ES is a summary of the aggregate subject judgments, the SJ_L and SJ_S values, for all ship courses in the 180° range, as expressed by Equation (5-4).

$$ES(t) = \sum_j SJ_{Lj}(t) + \sum_j SJ_{Sj}(t) \quad (5-4)$$

where:

t = the time in s

j = the ship course from COG -90° to COG $+90^\circ$.

The indices of SJ, which are distributed from 3 to -3 and estimated using the regression equation, are converted into the ES index from 0 to 6 [47]. The maximum aggregate value of the ES index is six multiplied by the 180° directions. The values of ES fall between zero for extremely safe and 1000 for extremely dangerous.

5.4.2 Development of the Methods

The methods described in the previous section do not consider the maneuvering initial condition for the assessment of the navigation safety. The condition may randomly change at the initial position of ship maneuvering owing to the change of environment disturbances. Therefore, the initial conditions for maneuvering are considered as environmental factors for the development of the proposed method. The distribution of the initial condition will affect

the distribution of ship courses and trajectories. The distribution of ship trajectories is used for estimating the difficulty of steering a ship in the research area and identifying the possibility of determining a safe route. This is a different approach implemented the proposed method. In the ES method, all of the 180° direction courses are considered. Conversely, EL is used for the safety evaluation of a specific trajectory. The proposed method includes the following methods: Distance Level (DL), Aggregate of Distance Level (AgDL), and Average Distance Level (AvDL), which represents the index of navigation safety of a certain position and course at a specific time, several possible positions and courses at a given time, and a possible trajectory at a period of time.

5.4.2.1 DL Method

A difficulty found in the implementation of the EL method is that the research on the estimation of stopping maneuverability for any kind of vessel has not hitherto been published. Moreover, the estimation of lateral force and yawing moment induced by a reversing propeller has been, similarly, not widely investigated. Therefore, in the proposed method, the SST and TTC parameters are replaced by an estimation of stopping distance (SD) and distance to obstacles (DTO).

The method is developed based on the DTO and SD. The DTO is calculated based on the subject ship position and course estimated using the MMG model. An algorithm is developed for obstacle detection and distance calculation along the trajectory. The DTO is the distance between the subject ship and obstacles including target ships, anchorage borderlines, shallow water, and port structures. The distance is calculated according to the procedure described below.

The first step of the algorithm is to detect the intersection between the ship's course and the straight line of an obstacle. The detection is performed based on the ship's course estimated using the MMG model. The ship's course is compared with the azimuths of the two endpoints of an obstacle's straight line. The positions of the endpoints of the straight line are converted into the coordinate system of the MMG model. The ship's course is calculated in the model based on changes in the ship's position in one-second increments. If the ship's course is between the azimuths of the two endpoints of an obstacle line, a cross point is calculated using Equations (5-5) and (5-6).

$$x_2 = \frac{(x_0y_1 - y_0x_1)(x_3 - x_4) - (x_0 - x_1)(x_3y_4 - y_3x_4)}{(x_0 - x_1)(y_3 - y_4) - (y_0 - y_1)(x_3 - x_4)} \quad (5-5)$$

$$y_2 = \frac{(x_0y_1 - y_0x_1)(y_3 - y_4) - (y_0 - y_1)(x_3y_4 - y_3x_4)}{(x_0 - x_1)(y_3 - y_4) - (y_0 - y_1)(x_3 - x_4)} \quad (5-6)$$

where:

x_0 and y_0 = the coordinates of the subject ship at time $(t - 1)$,

x_1 and y_1 = the recent coordinates of the subject ship at time t , and

x_3 and y_3 , x_4 and y_4 = the coordinates of the end points of the obstacle line.

The method is presented in Figure 5-1.

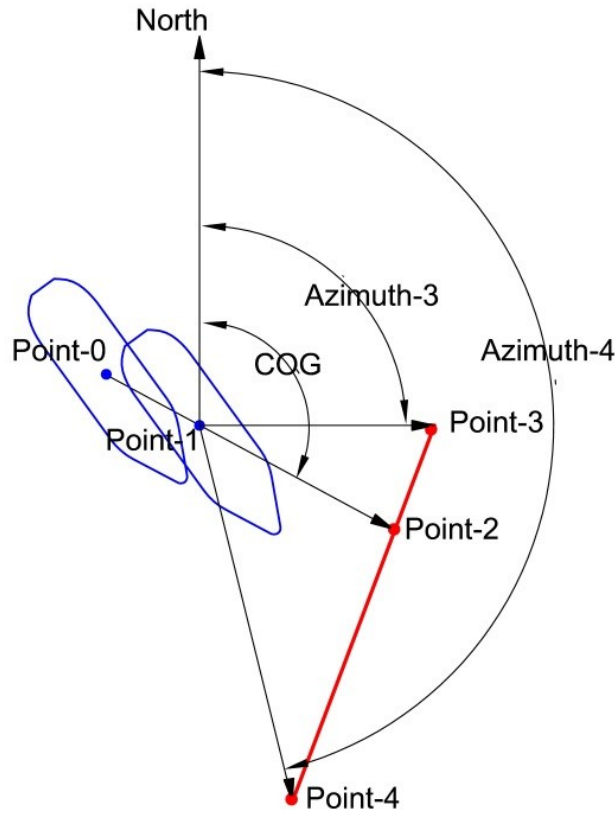


Figure 5-1 Method for detecting linear line of obstacle

Similar to the implementation of the EL method in this study, the stopping distance is also estimated based on the IMO Maneuvering Explanatory Notes [51] and depends on the ship type, machinery type, and ship length. The DL at time t , $DL(t)$, is defined as the following.

$$DL(t) = 1 - SD/DTO(t) \quad (5-7)$$

The greater the DL the higher the safety index of the ship. The ship is in an unsafe situation if the DL is negative.

5.4.2.2 Probable Paths

The AIS data used herein are obtained from an AIS receiver installed in cooperation with Kobe University, Japan, at the Institut Teknologi Sepuluh Nopember, Indonesia. The AIS data in the research area are analyzed and the probability density function (PDF) of the drift angle is provided. The yaw rate cannot be determined from the AIS data. Accordingly, the phenomenon of a small zigzag is simulated in the research area and the trend of the yaw is compared to the trend of the true heading of a straight path derived from the AIS data. The proposed method using AIS data analysis is shown by Figure 5-2. The distribution of the yaw rate of the appropriate small zigzag maneuver is trained as the random initial yaw rate in the simulated turning maneuver for the estimation of the possible paths.

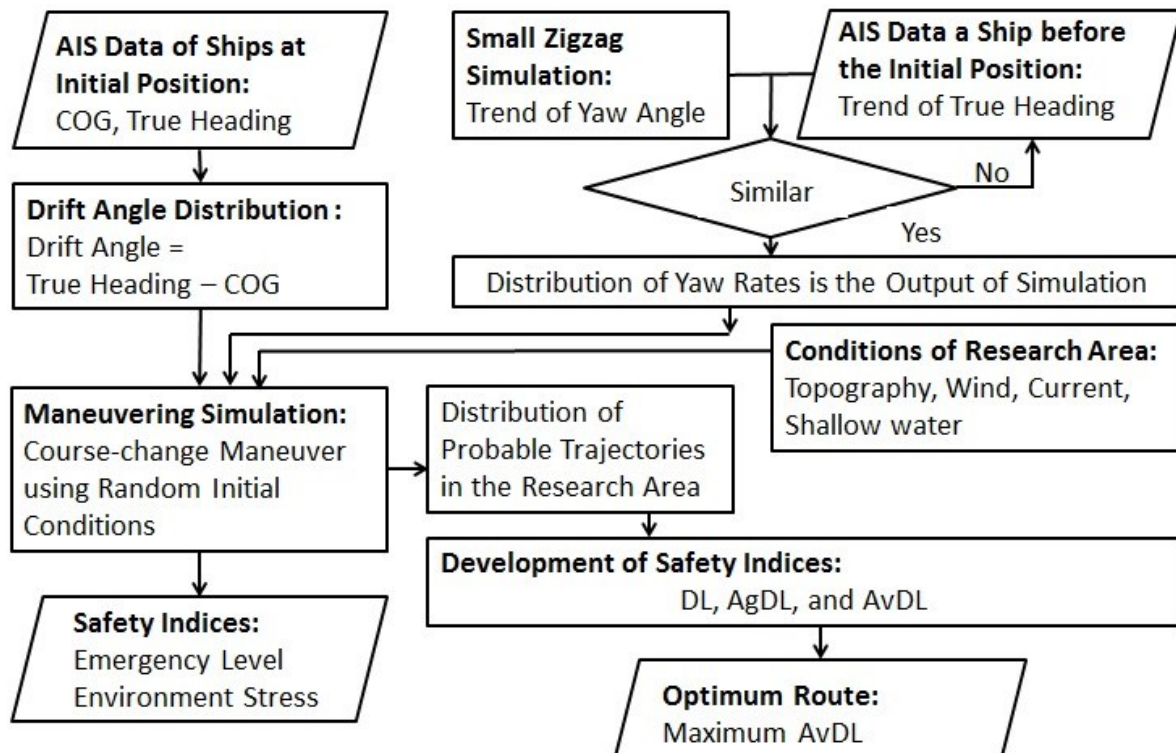


Figure 5-2 Proposed method

The possible paths are simulated using the MMG model by randomizing the initial yaw rate r based on the PDF. The initial speeds of the ship including surging speed u_{0i} , swaying speed v_{0i} , and yaw rate r_{0i} , are presented by Equations (5-8) to (5-10).

$$u_{0i} = U_0 \cos \mu_\beta \quad (5-8)$$

$$v_{0i} = U_0 \sin \mu_\beta \quad (5-9)$$

$$r_{0i} = (b - a)rand(1) + a \quad (5-10)$$

where

U_0 = the speed over the ground,

μ_β = the mean drift angle,

b = the maximum yaw rate,

a = the minimum yaw rate, and

$rand(1)$ = the random initial yaw rate based on a uniform distribution.

5.4.2.3 Aggregate and Optimum Distance Level

The aggregate of distance to obstacles (ADTO) is calculated by considering the distribution of the parameters based on the course probability. In this scenario, the initial condition of the ship to execute a turning maneuver between anchorage zones is randomly changed based on the distribution of the yaw rate at the initial position. The probability density function (PDF) of the initial yaw rate condition is analyzed according the phenomenon of a small zigzag on a straight course before taking the turning maneuver in the area.

The ADTO is defined as the summation of DTO_i multiplied by the probability of DTO based on the probability of a course P_{DTO_i} . The probability of a course depends on the PDF of the initial conditions. The ADTO and AgDL at time t , $ADTO(t)$ and $AgDL(t)$, are indicated by Equations (5-11) and (5-12).

$$ADTO(t) = \sum_{i=1}^n DTO_i(t)P_{DTO_i}(t) \quad (5-11)$$

$$AgDL(t) = 1 - SD/ADTO(t) \quad (5-12)$$

where:

t = the time in seconds,

i = the trajectory, and n is the number of trajectories.

The possible paths are simulated randomly based on the uniform distribution of the yawing speed obtained from the result of the small zigzag simulation. Accordingly, Equation (5-11) becomes Equation (5-13) as follows:

$$ADTO(t) = \frac{1}{n} \sum_{i=1}^n DTO_i(t) \quad (5-13)$$

The AgDL is essential to allow the determination of an optimal trajectory. The optimal trajectory is the trajectory having the maximum AvDL in the period T , as given by Equation (5-14).

$$AvDL = \frac{1}{T+1} \sum_{t=0}^T DL(t) \quad (5-14)$$

5.5 Results

5.5.1 Simulation in the Passage between Anchorage Zones

The passage between the anchorage zones was selected as the case study. The trajectory of the subject ship simulated in the passage located between the anchorage zones is indicated by the blue path in Figure 5-3. The red lines in the figure represent the obstacles consisting of the virtual lines of anchorage boundary lines, shallow water, and the port area. The ship is simulated with an initial speed of 7.6 kt and initial heading of 140°. The time series of the rudder angle used for the trajectory is indicated by the red curve in Figure 5-4. The ship course during the maneuvering in the area is presented in blue.

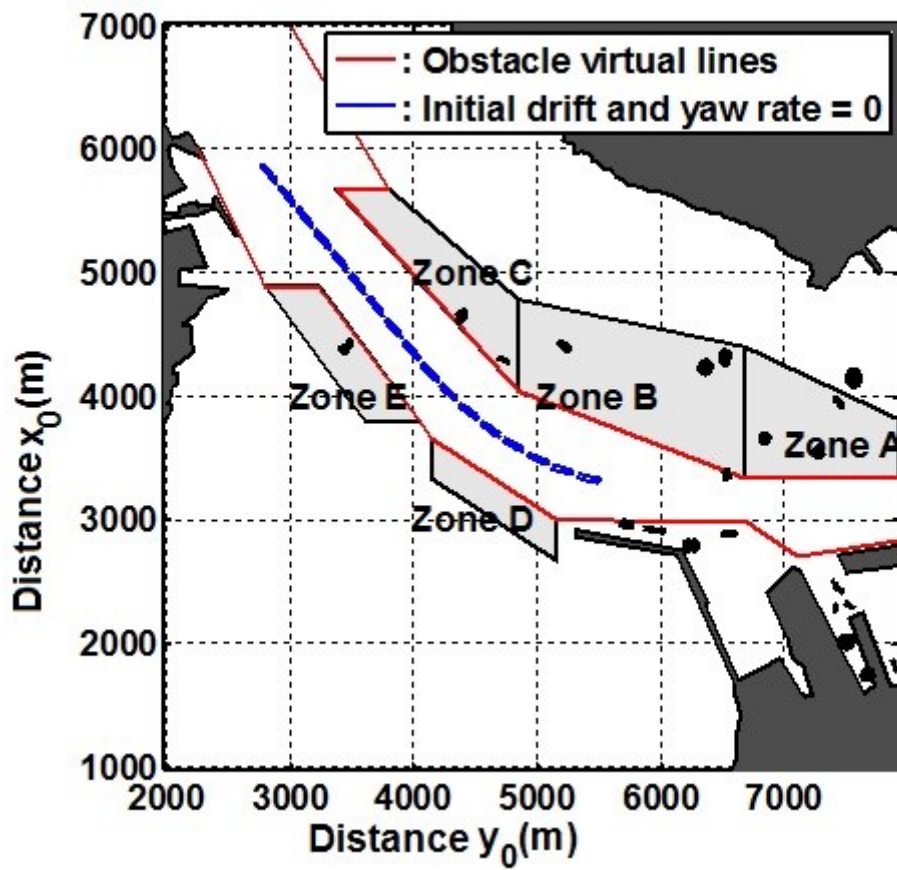


Figure 5-3 Trajectory using zero initial drift angle and yaw rate

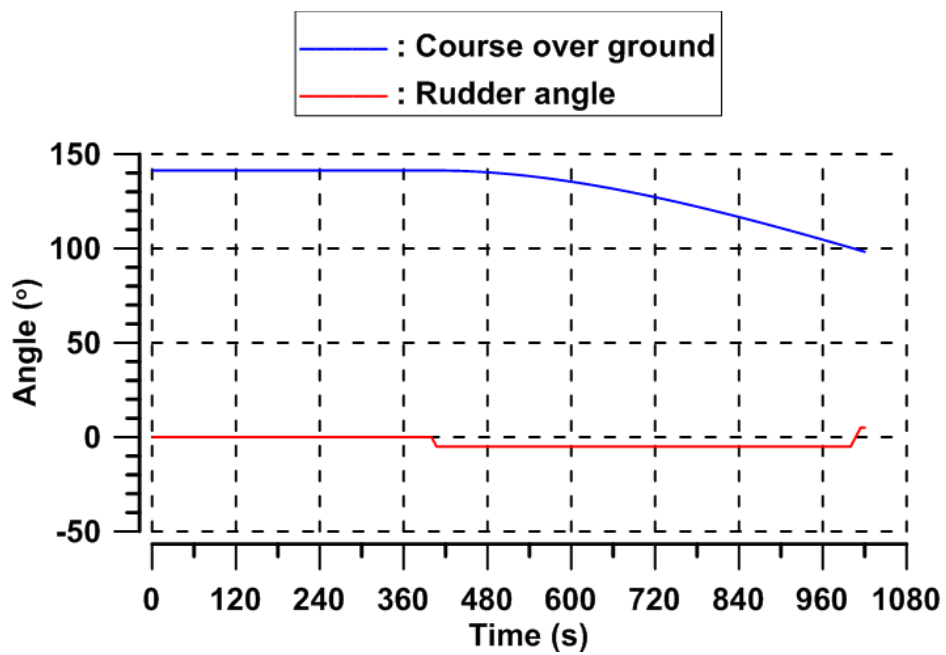


Figure 5-4 Time series of rudder angle and course over ground

5.5.2 Result of EL and DL Methods

The result of the safety indices EL and DL is presented in Figure 5-5. This figure illustrates that at the beginning of the simulation the stopping distance is shorter than the distance to the obstacle.

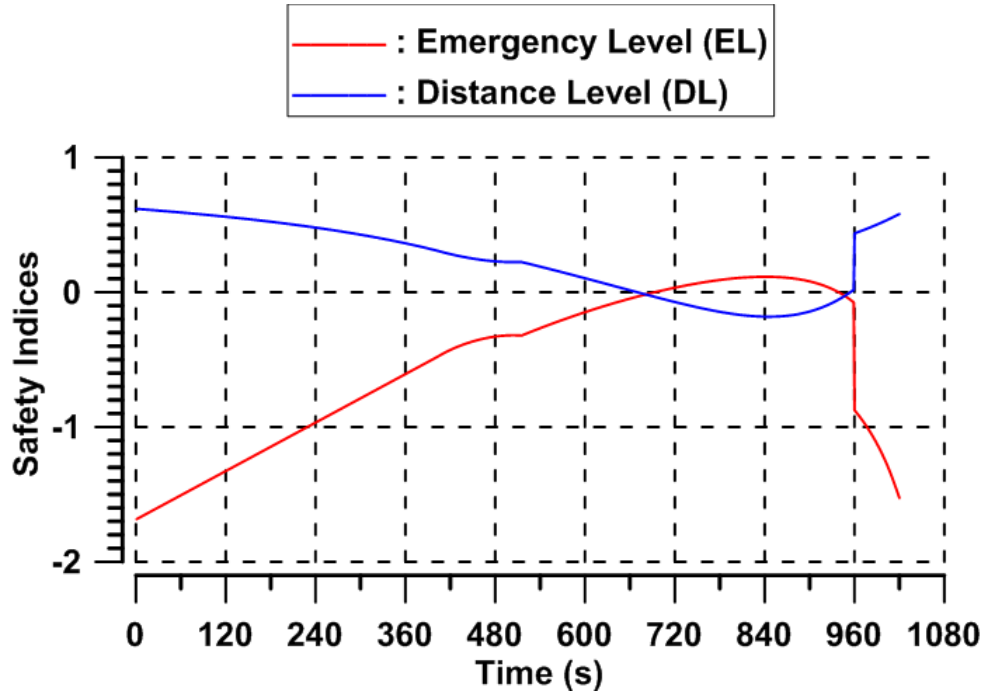


Figure 5-5 Time series of EL and DL

The ship leads to the Zone D and in safe situation because the EL is negative and DL is positive. The ship enters an unsafe situation when executing the turning maneuver and the course leads to the port area. This unsafe situation is indicated by the period between the intersections of the EL and DL curves, between 670 s and 954 s. The unsafe situation occurs when the ship is heading towards the first obstacle line of the port where four ships are approaching the berth. The ship returns to a safe situation at 955 s and the navigation safety significantly increases when the ship's course passes the first obstacle line of the port area.

5.5.3 Environment Stress (ES)

The difficulty of steering the ship in the area is illustrated by the ES time series in Figure 5-6. The ES is in a negligible condition, $ES < 500$, before the ship enters the passage between the anchorage zones. The ship enters a catastrophic condition, $ES > 900$, when it enters the passage at 189 s. The stress decrease to the critical condition, $750 < ES < 900$, and marginal condition, $500 < ES < 750$, when the course leads to the port area and then returns

to a catastrophic condition at 791 s. In this catastrophic condition, changing course between -90 to 90 results in the maximum unsafe situation for the ship because of the short distance to Zone B and the port area.

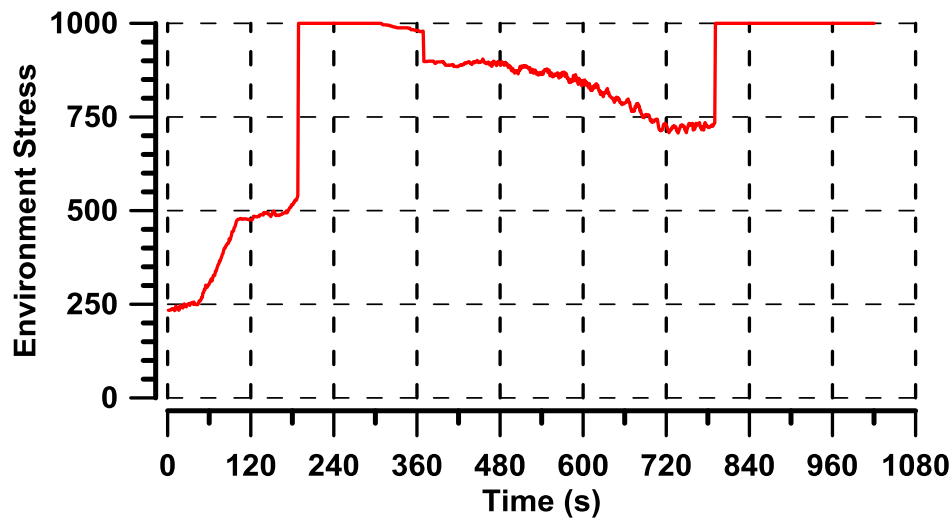


Figure 5-6 Time series of ES

5.5.4 Distribution of Initial Conditions

The drift angle of the ships at the initial position of the turning maneuver between the anchorage zones is calculated from the difference between the ship heading and COG derived from the AIS data. The yaw rate is determined from the time series of the yaw angle of a 2°/-2° zigzag maneuver of the subject ship. This is comparable to the trend of the true heading of an AIS-based trajectory of a ship belonging to the same class, in the area, before entering the passage between the anchorage zones. The distribution of drift angle and yaw rate belonging to class C ships are presented in Table 2-3. The distribution of drift angle was analyzed from 25 ships at the position of latitude -7.166, the starting position of the passage between the anchorage zones. The AIS data from January 1, 2011 to January 7, 2011 were used for the analysis. The number of ships entering the port was 42 ships per day on average; however, number of recorded ships belonging to class C at the position was 25.

5.5.5 The Aggregate Distance Level (AgDL)

A simulation was developed by setting the initial drift angle as the mean and randomizing 100 initial yaw rates based on the distribution presented in Table 2-2. The

random trajectories are indicated in blue in Figure 5-7. The trajectories indicate the possibilities for ships entering the anchorage zones.

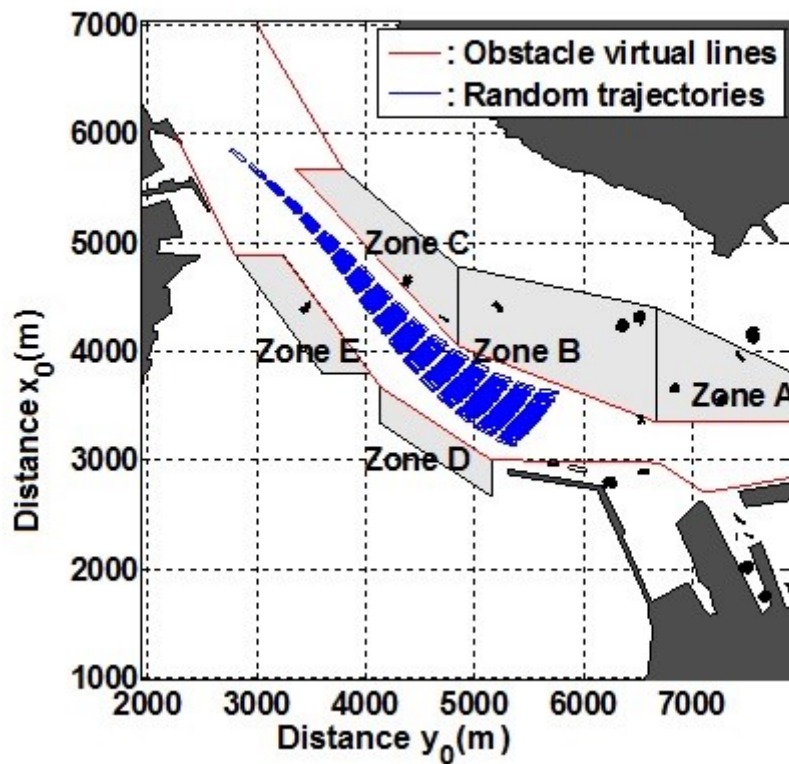


Figure 5-7 Probable trajectories based on distribution of yaw rate

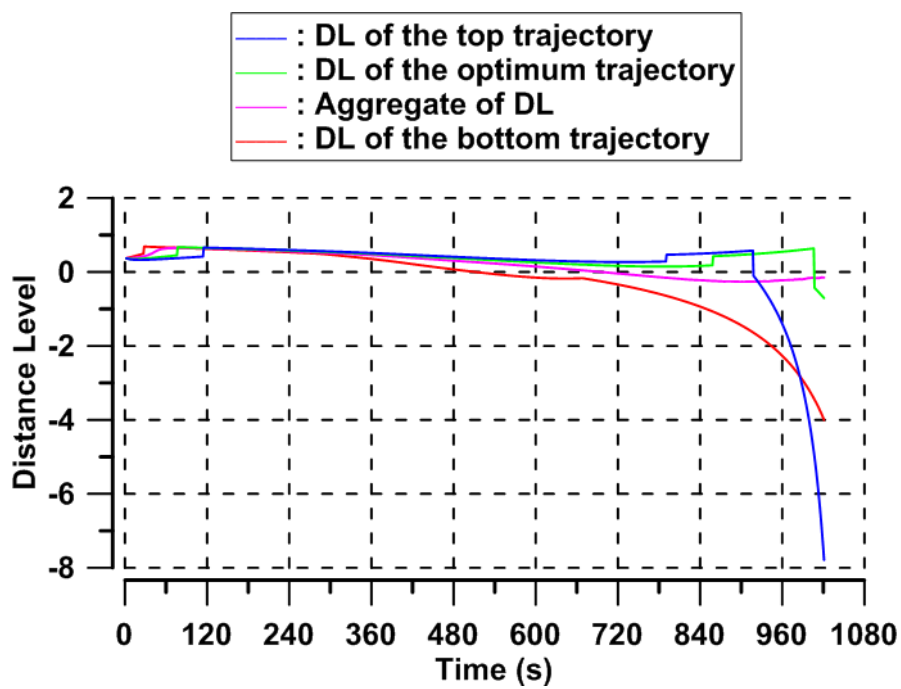


Figure 5-8 Time series of DL of trajectories

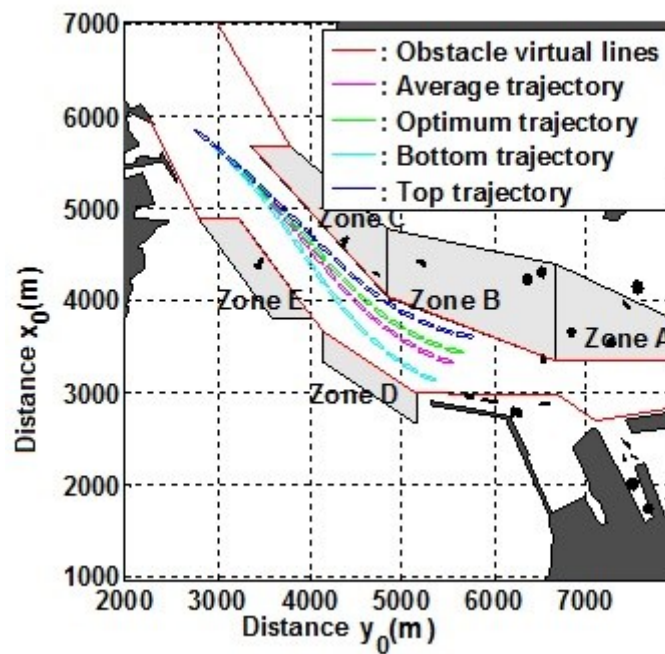


Figure 5-9 Optimum trajectory

The AgDL of the 100 paths is presented in Figure 5-8 in magenta. The AgDL is compared to the DLs of the bottom and top as well as the optimum trajectories. The bottom trajectory is the path closest to anchorage zone D and the top trajectory is nearest to zone B as presented in Figure 5-9. The DL time series of optimum trajectory and the trajectory are presented in green in Figures 5-8 and 5-9.

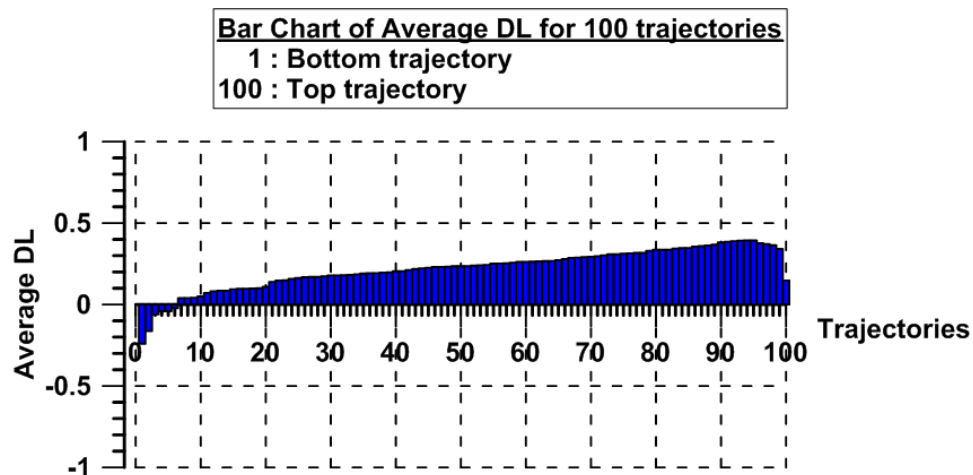


Figure 5-10 AvDL of trajectories

The optimum trajectory is the trajectory having the maximum AvDL. The AvDL of the 100 possible trajectories is represented by the bar chart presented in Figure 5-10. By

comparing the DL time series of the optimum trajectory and the AgDL in Figure 5-8, it is demonstrated that the optimum trajectory can be improved by modifying the ship's course during the last 15 s of the simulation. The port-side turn using -5° of rudder angle as indicated in Figure 5-4 must be changed to a starboard turn 15 s earlier.

5.6 Discussions

The DL, AgDL, and AvDL indices for the assessment of navigational safety are implemented according to the following steps.

1. Probable trajectories are simulated using ship maneuvering estimation based on the MMG model.
2. The time series of DL indices for all trajectories are calculated based on the stopping distance of the ship and the time series of the distances of ship to obstacles. In this study, the stopping distance is calculated based on IMO equation.
3. The optimum trajectory is determined by using the AvDL index. The trajectory with the maximum AvDL is considered as the optimum trajectory.
4. The comparison of the time series of DL for the outer trajectories to the time series of AgDL is important step in order to seek the optimum trajectory.
5. The possibility to find the safe trajectory is available if at least one of the DL time series of the outer trajectories is located in the positive area

The methods have been implemented for the maneuvering of a subject ship in the developing port area in the Madura Strait. The optimum trajectory has been proposed based on the existing condition of the port area.

5.7 Conclusions

The navigation safety indices of Emergency Level (EL) and Environment Stress (ES) were implemented for the passage between anchorage zones in the Madura Strait and a new method of navigation safety-index was proposed. The results of the study are as follows.

1. The implementation of the ES method indicated that the difficulty of steering the ship before the passage between anchorage zones was negligible and increased to critical and catastrophic in the passage.
2. The EL method was implemented using the estimation of stopping time based on the IMO prediction equation of stopping distance. The implementation of this method in the research area indicated that the subject ship was in an unsafe situation during the turning maneuver.
3. A new method for DL, AgDL, and AvDL was proposed to identify the safest possible route and determine the optimal trajectory. The method was developed by calculating the aggregate distance to obstacles for all of the possible trajectories. The possible trajectories were simulated based on the distribution of the yaw rate in the research area. The distribution was analyzed using AIS data. The distribution was processed for the estimation of possible trajectories using the MMG model.

A new navigation safety index was introduced and the safest route in the research area was determined by analyzing the AIS data and considering the environment disturbances based on the MMG model. Further study will concentrate on the following.

1. Application of the proposed method to evaluate the danger area in other ports.
2. Implementation of a method to redesign ship routes in other developing ports in the country.
3. Usage of the method for the prediction of collision probability in port areas.

Improving the method by using the estimation of stopping distance based on the simulation of full crash astern maneuver is the future work of the study.

Chapter 6

Collision Probability upon Taking Astern Maneuvers

6.1 Introduction

Tanjung Perak Port area is located in the Madura Strait between Java Island and Madura Island, in Surabaya, east of Java, Indonesia. The port plays an important role as the central port of Indonesia. The port provides transportation services to and from the center of international trading in Singapore, as well as domestic trading services between the western and eastern parts of Indonesia. The port is expected to handle ships without transit in Singapore. Accordingly, larger ships could be handled. A multipurpose port was built in Lamong Bay near to the Tanjung Perak Port. The positions of the ports and anchorage zones are shown in Figure 6-1. The trajectory of a ship on the fairway is plotted in Figure 6-1 based on the automatic identification system (AIS) data. The positions indicated in blue are created as the limit of 6 areas representing 3 paths of course keeping A, C, and E, and 3 paths of turning B, D, and F.

Figure 6-1 shows that two anchored ships are located out of the anchorage zones and close to the fairway, indicating an increasing number ship calls. The increasing number of ship calls and the lack of traffic scheme in the developing port area will increase the number of collision candidates, and the causation probability, and subsequently will increase the number of ship collisions. The causation probability of ship collisions in the Madura Strait is about 1.08×10^{-4} [52]. This is higher than those in ten fairway segments in Norwegia which varied from 0.3×10^{-5} to 1.5×10^{-5} [9]. The probability represents the frequency of failing to

avoid a collision when on collision course. The high causation probability also denotes the high probability of ships losing control. The high number of ship calls and ships losing control as well as the limited area will make course changes more difficult when the ships are exposed to a ship-ship collision situation. Besides course changes and course keeping, a crash astern maneuver may be chosen by the navigator to avoid accidents.

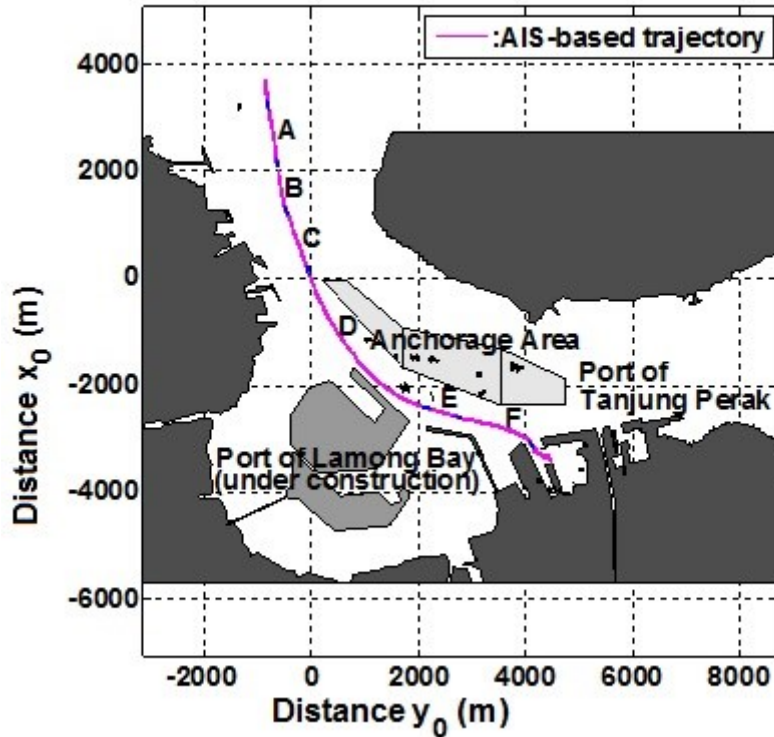


Figure 6-1 Ship trajectory in the research area

This study aims at developing a method to estimate the probability of collision when using a crash astern maneuver. The proposed method was developed based on the combination of the two typical methods introduced by Fujii [53] and Kristiansen [9], and the concept of PAW introduced by Inoue [7]. The frequency of a subject ship on collision course is estimated based on the distributions of initial speed and initial yaw rates. The uncertainty of the initial conditions significantly affects the paths of the maneuvers [46]. The trajectories are estimated using mathematical maneuvering group (MMG) model and initial conditions of speed and yaw rates are analyzed from automatic identification system (AIS) data. The aim of this study is to propose a method for estimating the probability of collision resulting from crash astern maneuvers in the research area of a ship on a collision course that attempts crash astern maneuvers.

6.2 Literature Review

The formula used for the assessment of collision risk is shown in the equation (6-1), [19].

$$R = PC \quad (6-1)$$

where:

R = the collision risk

P = the probability of collision

C = the factor representing the consequences of collision such as collision energy losses.

Several researchers have introduced methods for estimating the number of collision. Generally, the methods are developed based on Fujii's model [53], where the number of expected collision is calculated from the number of collision candidates multiplied by the probability of failing to avoid a collision when on a collision course, as shown by the equation (6-2).

$$N_{coll} = N_A P_C \quad (6-2)$$

where:

N_{coll} = the number of collisions for a given time period

N_A = the number of encounters during the time period

P_C = the probability of failure of collision avoidance, generally known as causation probability.

In this approach, the number of collision candidates is estimated based on an encounter segment of the lateral distribution of the ship's trajectory. The probability of collision avoidance failure, the causation probability, is estimated based specific error situation analysis on several factors leading to the probability of wrong action and steering failure.

In another approach, the probability of steering failure is defined as the probability of a loss of control. It estimates the collision probability by multiplying it with the probability of

a ship collision upon the loss of vessel control [9]. In this method the probability of loss control is determined from historical data. The probability of a collision upon the loss of vessel control is calculated using geometrical probability based on dimensions of fairway and ships, traffic density, and ships' speed, as well as the type of collision. In this approach, first, the probability of collision P_a , is determined based on the historical accident data and second, the probability of collision upon the loss of vessel control P_i is calculated based on geometrical probability of collision. Finally, the probability of loss control P_c in the port area is determined. Collision probability is defined as the probability of a loss of control P_c multiplied by the probability of an incident (the probability of accident upon the loss of vessel control) P_i [9] as follows:

$$P_a = P_c P_i \quad (6-3)$$

where the indexes denote accident (a), loss of control (c), and impact (i). In this approach, the probability of loss control seems to be treated as the collision candidate frequency which is determined based on the historical statistic data. The probability of incident, probability of accident upon the loss of vessel control acts as the probability of failing to avoid accident. However, the method used for determining the incident probability is different from that used for estimating causation probability in the previous approach. It was used in the first approach to calculate the collision candidate frequency, which depends on the type of encounter, fairway dimensions, and the speed and dimensions of ships, based on a geometrical probability.

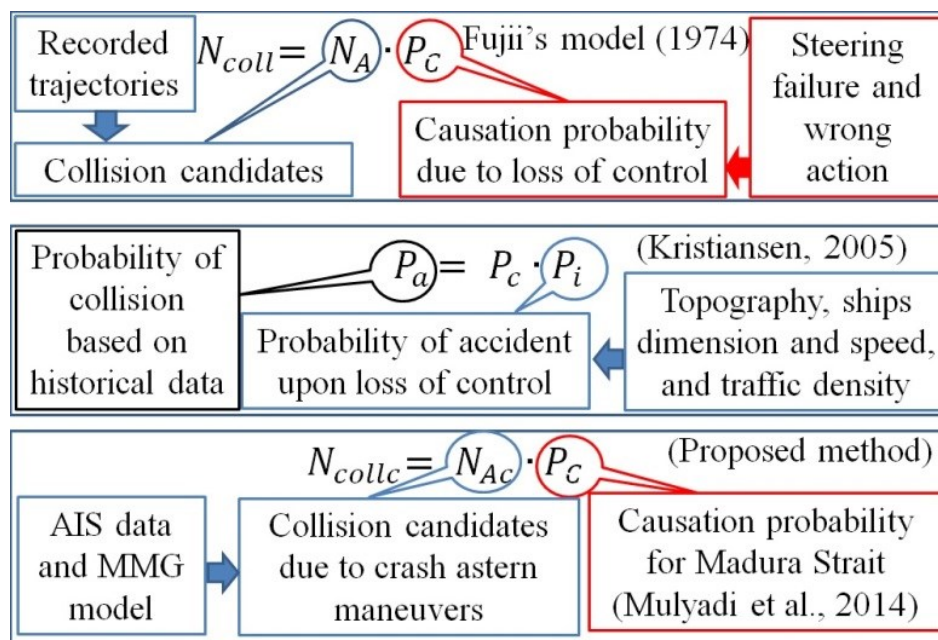


Figure 6-2 Flow chart of existing and proposed methods

Figure 6-2 shows the approaches of the described methods and the proposed method. Both the existing methods do not specifically show the probability of collision upon using crash astern maneuvers, which may be adopted by navigators to avoid a collision in dense traffic. The lateral deviation of the maneuvers may be considered as a wrong action included in the causation probability, and a losing control in the first and second approaches, respectively. However, the specific estimation of probability of a ship on a collision course when performing crash astern maneuvers has not yet been analyzed.

This paper proposes a method to estimate the probability of ship on a collision course, upon taking crash astern maneuvers, based on a new potential area of water (PAW) for maneuvering. The PAW for maneuvering is defined as the water area that would be used before the intended ship's movement is achieved, assuming that the navigator will encounter an emergency involving the application of crash astern maneuver or such other emergency action as may be necessary should the ship encounter an unexpected situation during the maneuver [7]. The number of collision candidates due to crash astern maneuver is the number of ships taking crash astern maneuvers multiplies by the probability of ship on collision courses performing crash astern maneuvers. The number of ships taking crash astern maneuvers is the number of ships entering the research area multiplied by the probability of them taking crash astern maneuvers. However, the probability of taking a crash astern maneuver is not discussed in this paper. The PAW was developed by superimposing the ship paths by their positions when crash astern maneuvers are ordered [7]. The new PAW developed in this paper is developed not only by the positions when the maneuvers are ordered but also by the distribution of initial speed and initial yaw rate.

6.3 AIS Data

The AIS data is taken from 25 entering ships belonging to class C at the position of the research area. Additional data were analyzed from maneuvering simulation. The data has been presented in Section 2.3.3.

The number of ship calls in the port area on a peak day in January 2011 is more than 120 ship calls as shown in Figure 2-9. Number of entering ships is higher than leaving ships causes the high number of anchoring ships as indicated by the ships anchoring out of the anchorage zones as shown in Figure 6-1. Number of entering and leaving ships is identified

from AIS data by distinguishing the ship courses in the research area. The average number of entering and leaving ships per day is 49 and 42, respectively.

The distribution of ship speeds in the 6 areas is presented in Table 2-5. The distribution fits to normal distributions with a mean of between 10 to 5 knots decreasing from area A to area F. The average ship speed is more than 9 knots before entering the anchorage zones in area A, B and C. It is more than 7 knots in the area between the new port and anchorage zones, area D, and about 6 knots in the existing port area, area E and F.

6.4 Methods

The method of MMG model has been presented in Section 3.2. In this study the crash astern maneuvers are simulated using the MMG model. Originally, the concept of PAW for crash astern maneuvers is introduced as an area covered by possible paths of a ship upon taking several emergency actions of crash astern maneuvers. The possible paths are developed based on the position when maneuvers are ordered [4]. Each position actually represents a specific course, speed, and yaw rate. However, a PAW is introduced as the superposition of the paths of the maneuvers ordered at several initial positions. This paper proposes a new PAW that is developed based on not only the position when maneuvers are ordered but also the distributions of the speed and yaw rate in an area of the positions. The distribution of ship's speed is analyzed from AIS data. However the distribution of yaw rate is not provided in the AIS data. Accordingly, a method is proposed to estimate the distribution of yaw rate in the research area as following. The proposed method using AIS data analysis is shown by Figure 6-3.

1. The subject ship is simulated in the research area to follow the trajectory of a ship belonging to the same class derived from AIS data.
2. The trajectory and time series of the subject ship's yaw angle should be similar to those derived from AIS data.
3. The trajectory is divided into several paths of areas. The distribution of yaw rate of the subject ship in an area calculated in the MMG model is analyzed. The distribution is treated as random initial condition of crash astern maneuvers taken in the area.

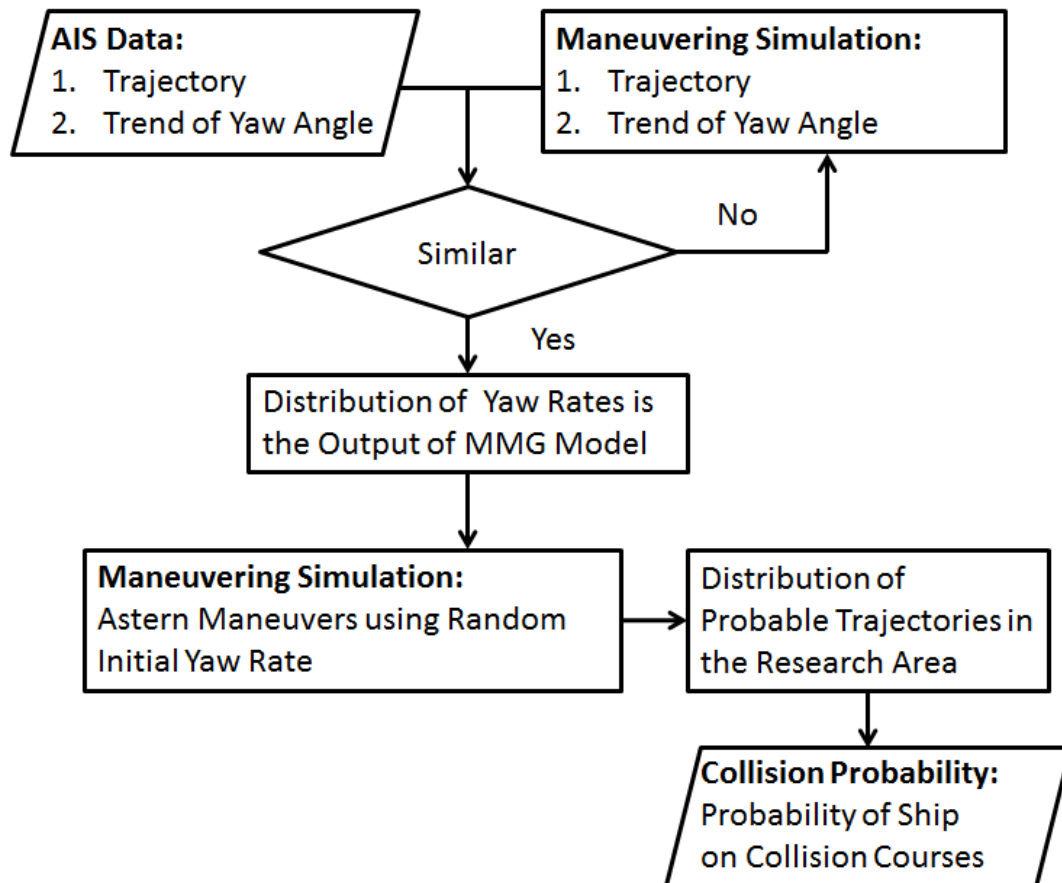


Figure 6-3 AIS data analysis

6.5 Results

The distributions of yaw rate of the subject ship in the 6 areas are estimated in the simulation using the MMG model to follow the trajectory of an entering ship plot based on the AIS data. Time series of rudder angles of the subject ship following the trajectory of the entering ship is shown in Figure 6-4 and the comparison of the trajectories are presented in Figure 2-4. Figure 2-4 shows that subject ship's trajectory is almost the same as the entering ship's trajectory. The subject ship's time series of yaw angle results from the MMG model are also almost the same with the entering ship's true heading derived from AIS data, as presented in Figure 2-5.

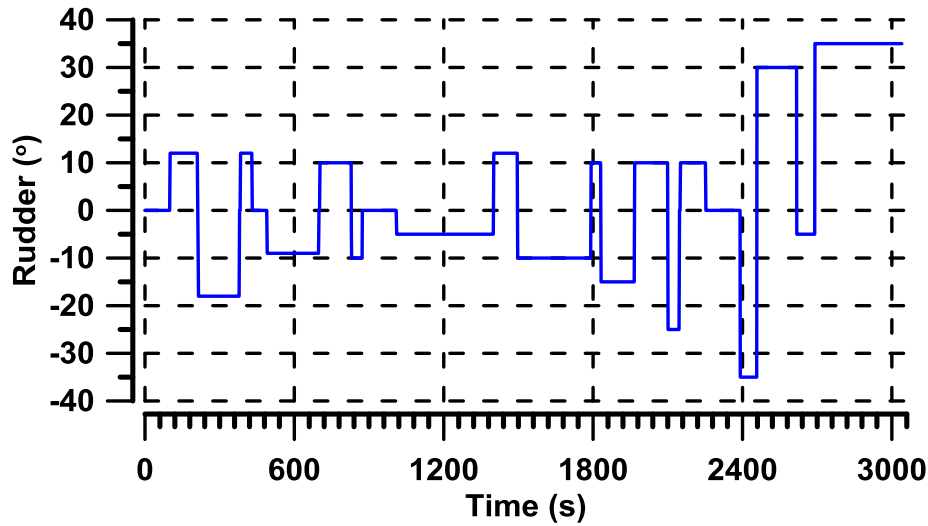


Figure 6-4 Time series of rudder angle

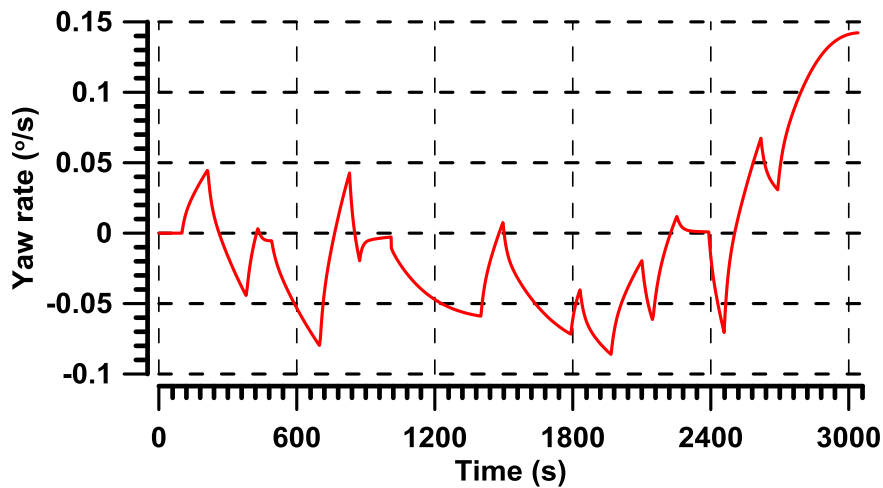


Figure 6-5 Time series of yaw rate

The time series of yaw rates of the subject ship based on the MMG model are shown by Figure 6-5 and the distribution of the yaw rates in the 6 areas are fit to normal and uniform distributions as listed in Table 2-4. Based on distribution of yaw rates presented in Tables 2-4, the initial of yaw rate, at the time of reversing the propeller is randomized. The reversing propeller is ordered at 4 positions in each area. Three types of crash astern maneuvers including slow, half, and full are simulated for the subject ship. The PAW of slow, half and full astern maneuvers based on the random value of initial yaw rate are presented in Figure 6-6.

Figure 6-6 shows that the PAW represented in red, becomes smaller when entering the area of Tanjung Perak Port, areas E and F, because the speed significantly decreases. The time series of ship speed is presented in Figure 6-7.

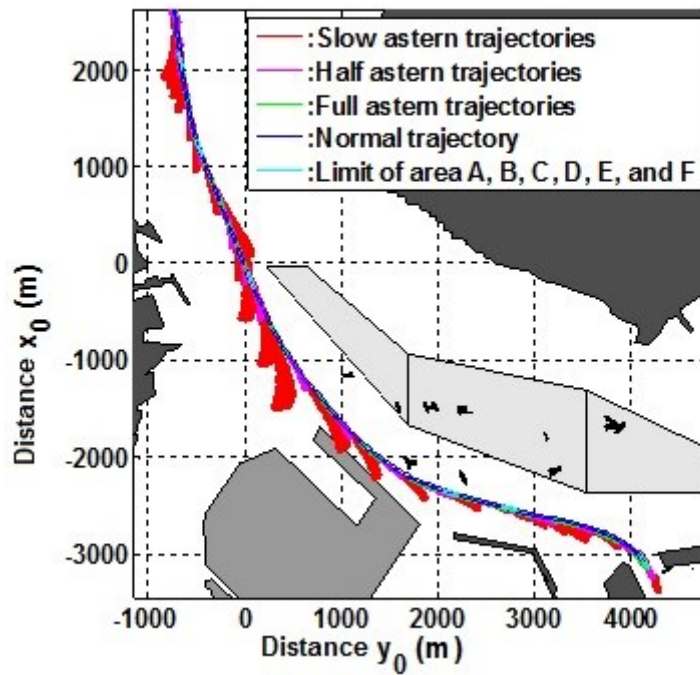


Figure 6-6 The PAWs by position and initial yaw rate

In area B, the PAW of slow crash astern maneuver covers the opposite line of the fairway lying at the port side of the entering ship. Some of the possible paths enter the exiting lane of the 100 m wide fairway. In areas C and D, the PAWs do not cover the opposite lane but enter the area of Lamong Bay Port. In area D, the PAW cross the line of port structure, which means the ship collides with the structure.

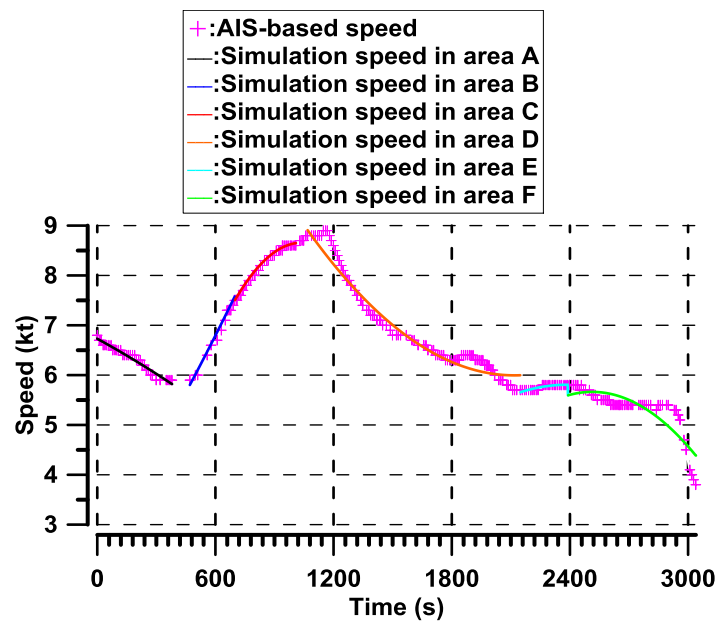


Figure 6-7 Time series of ship speed

6.6 Discussions

Area B is the area where a course alteration is taken before a short straight path of area C and the long turning path of area D. Four positions are selected in area B as initial positions which are when the crash astern maneuvers are ordered at the simulation times t , of $t = 410$ s, $t = 500$ s, $t = 590$ s, and $t = 680$ s. In area B, taking a slow crash astern at the last initial position, $t = 680$ s, caused a PAW covering the opposite lane as shown in Figure 6-8. However, if a half or a full astern maneuver is ordered, the lateral deviation is not significant. The maximum lateral deviation was only 0.24 times ship width B , and $0.13B$, for the half and full astern maneuvers, respectively. It is small deviation if it is compared to the width of the lane which is 100 m, about $3B$. Dangerous situation will occur if a slow crash astern is ordered. The distribution of lateral deviation from the normal position is shown as bar chart presented in Figure 6-9. The distribution fits to uniform distribution with maximum deviation of $4.165B$ and minimum deviation of $2.114B$. About 77% of the possible paths will enter the opposite line by considering that the allowable lateral deviation is half of lane width which is about $2.5B$.

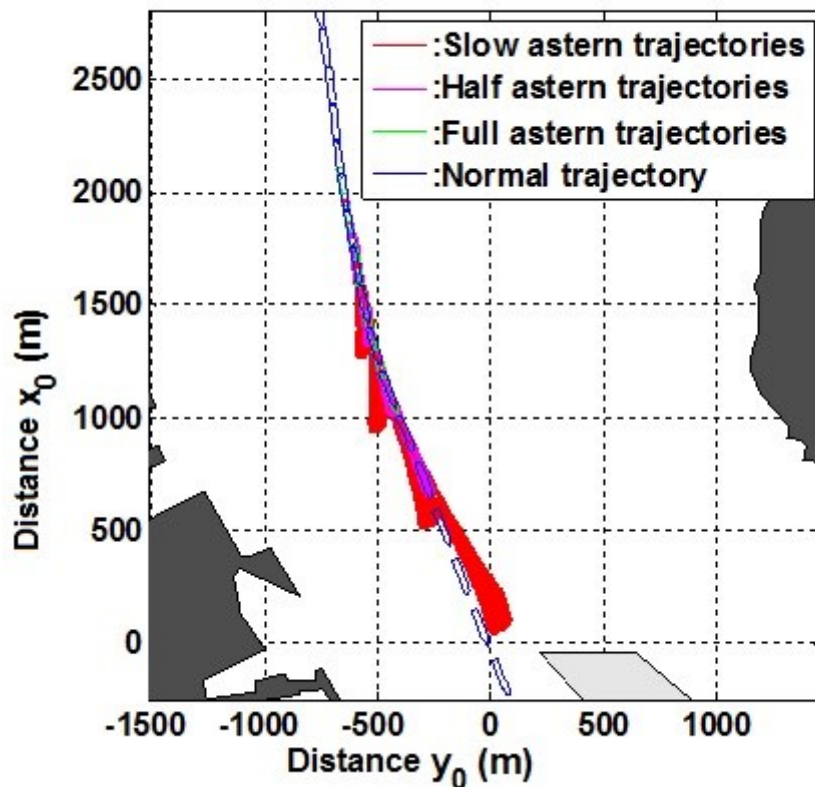


Figure 6-8 The PAWs by initial yaw rate in area B

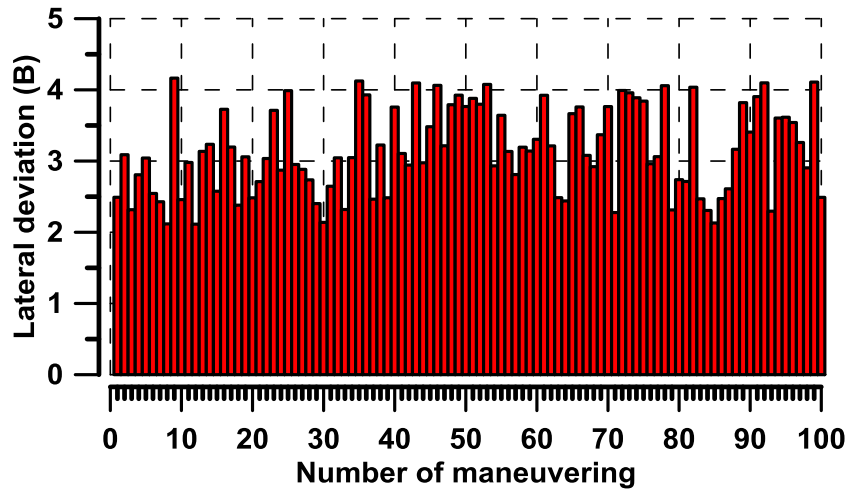


Figure 6-9 Bar chart of lateral deviation for slow crash astern at $t=680$

Area D depicts a long turning path located between anchorage area and the new port. If a slow crash astern maneuver is taken at positions between the first and second initial positions of area D, at $t = 1250$ s and $t = 1500$ s, the PAWs will cover the structure of Lamong Bay port. The ship's speeds at the initial positions are 7.98 and 7.00 kts, respectively.

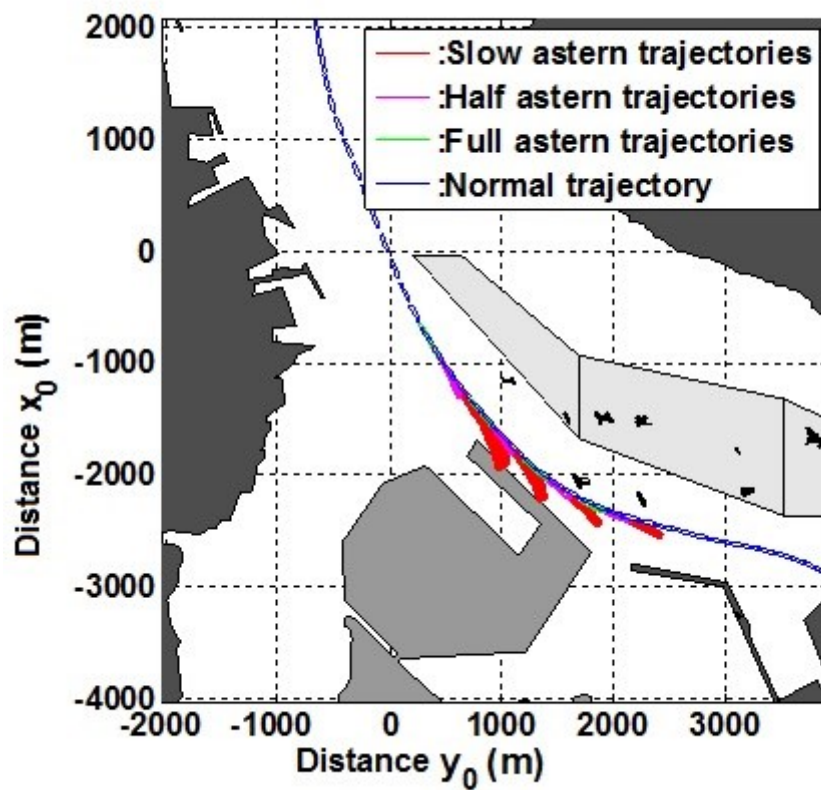


Figure 6-10 The PAWs by initial yaw rate in area D

Figure 6-10 shows, at the same of yaw rate distribution, the lower the initial speed the smaller the PAW. The bar chart of lateral deviation from the normal position of simulation of the PAW of initial position at $t = 1250$ s is shown in Figure 6-11. The distribution of the lateral deviation at this position fits to a normal distribution with the mean of $-5.894B$ and the standard deviation of $0.342B$. The minus means the ship deviates to the starboard side. The distance between the fairway and the Lamong Bay port's structure is about $4.9B$ and all of the possible paths on the PAW attack the port structure. However, the maximum lateral deviation for half and full crash astern are $1.9B$, and $0.23B$, respectively.

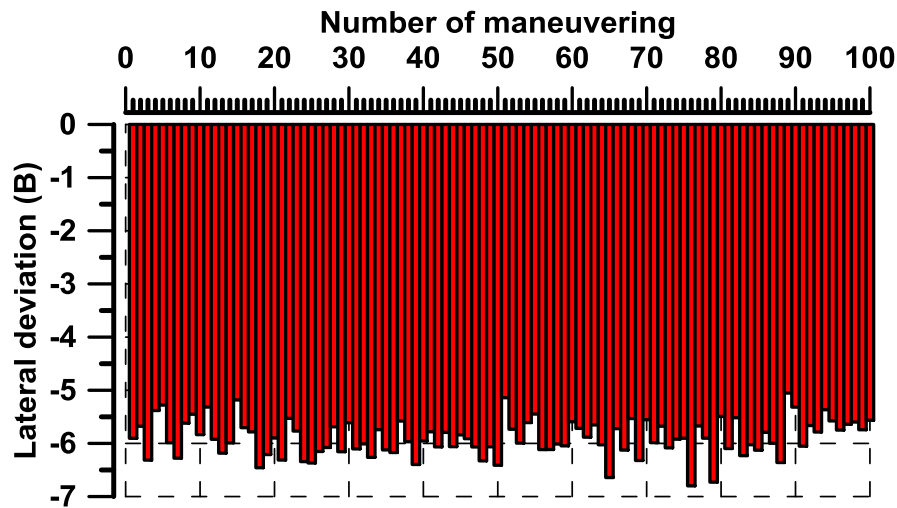


Figure 6-11 Bar chart of lateral deviation for slow crash astern at $t=1250$

The initial speeds at the two others initial position, at $t = 1750$ s, and $t = 2000$ s, are 6.35 and 6.03 kts. The maximum lateral deviations at these positions are $3.14B$ and $1.64B$. The deviations are less than the distance between the fairway and port structure. It means that the safe speed at this area is around 6 kts. The probability of ships on collision courses of attacking the new port structure upon taking a slow crash astern maneuver is about 50 %. It is estimated based on the probability of ships having speed higher than the safe speed upon entering the existing port area, area E, as presented by Table 2-5.

6.7 Conclusions

A new method of developing the PAW is introduced. The method is developed based on the position when the maneuver is ordered and the distribution of yaw rate in the area of the position. The distribution of yaw rate is estimated using a maneuvering simulation and

AIS data. The new PAW is implemented to propose a method to estimate the probabilities of ship on collision course upon taking crash astern maneuvers. The methods were implemented in the Madura Strait and conclusions obtained from the analysis of PAW in the research area are as following:

1. Area B, the area located before the anchorage zones, and area D, the area between the anchorage zones and the new port of Lamong Bay, are considered danger areas.
2. The accident probability of the subject ship on collision courses upon taking a slow crash astern maneuver at the end part of area B will be 77% if the initial speed of the maneuver is about 8 knots.
3. The subject ship will collide with the structure of the new port upon performing the maneuver at the first half of area D.
4. The maximum safety speed of the subject ship to avoid collision with port structure is about 6 knots.
5. The probability of ships on collision courses at the port area is estimated based on the distribution of ships' speed in the area, and the probability of ships to collide with the new port structure upon taking the slow crash astern maneuver is 50 %.

The subsequent phase of this research will analyze the probability of ships taking a crash astern maneuver, develop the PAW for maneuvering of other types of ships, and analyze the implementation of the method in any other developing port areas.

Chapter 7

Collision Risk Estimation in New Two-Lane Canal

7.1 Introduction

This paper proposes a simulation-based method to estimate collision risk for a ship operating in new two-lane canal. According to rule 9 of the Colreg-72 navigation rules, in a narrow canal, a vessel shall keep as near to the wall that lies on its starboard side [54]. However, a busy harbor entered through a narrow canal still presents impact hazards in a certain conditions. Certain conditions in a two-lane canal, such as a head-on situation in the straight part of the canal during an overtaking maneuver and large curvature of a turning maneuver in the bend part of the canal, could lead to accidents. In the first condition, the ship alters its own course to the port side to overtake another ship in the same lane but the course altered is too large and hits the wall of the canal. In the second condition, the target ship may take an excessively large turn on the bend part of the canal, causing collision with the ship on the opposite lane. Collision risk is represented as the risk of damage to the ship structure and includes the probability of impact accident and severity of structural damage. Predictions of collision probabilities in a two-lane canal have been developed based on a simulation of ship maneuvering using a maneuvering modelling group (MMG) model and automatic identification system (AIS) data. First, the propeller revolution and rudder angle of the subject ship are simulated to determine safe trajectory in the canal. Second, a method to estimate the probability of impact accidents is proposed. The structural consequences of the impact accident are measured as collision energy losses, based on the external dynamics of ship collision. The research area of the two-lane canal is located at the Madura Strait between

the Java and Madura islands in east Java of Indonesia, as shown by the red line in Figure 7-1. A project for developing a new port and dredging a new two-lane canal to facilitate an increase in the number of ship calls is currently underway in the research area. Figure 7-1 shows the ships' trajectories plotted using the AIS data as on January 1, 2011. The trajectories are mostly seen to be coming out of the canal, confirming that it is shallow and needs to be dredged.

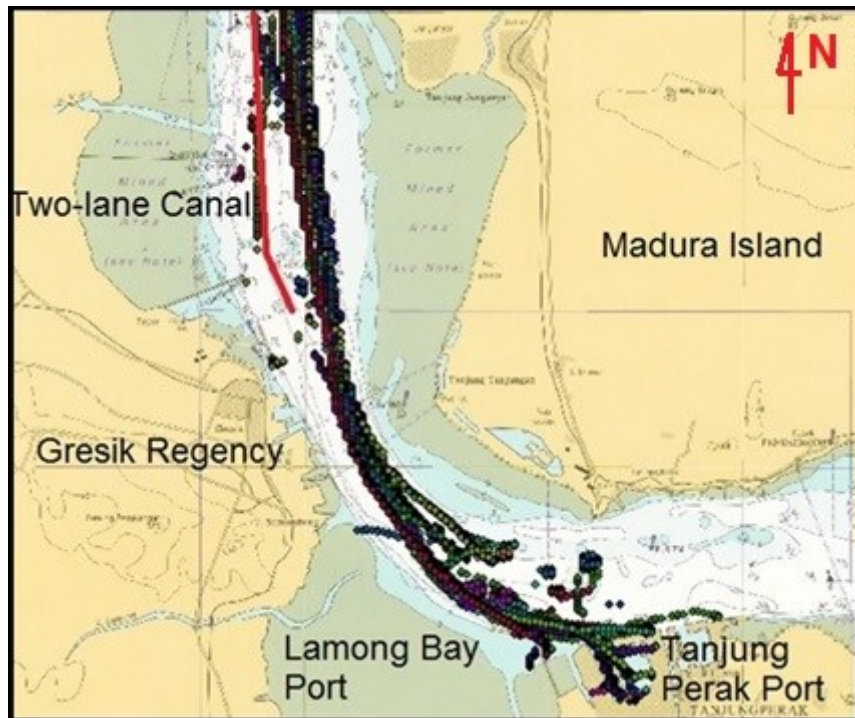


Figure 7-1 Research area of the new two-lane canal

This study has contributed to the development of port guidance in terms of safe maneuvering parameters for the developing port area. The paper also discusses a method to predict the probability of accidents using the MMG model by considering the environment and AIS data. The calculation of collision risk will provide guidelines for the maximum speed of a ship proceeding in the two-lane canal.

7.2 Literature Review

The author commenced the study by developing a Maneuvering Modelling Group (MMG) model and using Automatic Identification System (AIS) data to investigate the uncertainty in ship maneuverability in the port area [46]. This model was improved by

considering the effect of shallow water and disturbances including current and wind effect. The improved model was implemented to analyze the (a) navigation safety across anchorage zones in the developing port area of Tanjung Perak, Surabaya, Indonesia [38]; and (b) maneuvering parameters of a target ship entering the area, to avoid potential areas of water (PAW) for maneuvering [37]. The new Lamong Bay Port, chosen as the research area, is presently at the developing stage. In addition to being used to calculate emergency levels, the MMG model was used for calculating the environmental stress on navigation safety, a new equation for which was proposed for the research area [55]. Furthermore, the MMG model and AIS data were applied to evaluate the design of a two-lane canal at the entrance gate of the port area [56].

This paper is linked to the previous paper with regard to the research area and safety concern. The paper focuses on the development of a method for predicting the collision probability (using the MMG model and AIS data) and its consequences, namely, collision energy losses. Collision risk is calculated based on a common concept, as below [19].

$$R = PC \quad (7-1)$$

where R is the collision risk; P is the probability of collision; and C is the factor for collision energy losses, representing the consequences of collision in this paper.

Collision probability models are of two types: static and dynamic [19]. The probability of collision from the static model is presented as

$$N_{coll} = N_A P_C \quad (7-2)$$

where N_{coll} is the number of collisions for a given time period, N_A is the number of encounters during the time period, and P_C is the probability of failure of collision avoidance, generally known as causation probability. The static critical distance of the encounter situation is defined in literatures as a function of several quantities, namely, geometric collision diameter (which depends on the length, width, encounter angle, and vessel speed [57]), the typical distance (0.5 NM) at which ships come within close quarters of each other [58], and the minimum distance to collision, MDTC, (that distinguishes vessel types and depends on the encounter angle and the ships' maneuverability [18]). The probability of ship collision in a fairway during head-on, overtaking, and crossing maneuvering operations was analyzed [9].

A number of researchers have introduced probability models for dynamic collision, which use system simulation of ship traffic in the time domain, based on routes. One of these methods uses Monte Carlo simulation to analyze the collision candidates [10]. Furthermore, the interaction counting model for collision candidates is developed based on the models of Pederson [59], and Fuji and Shiobara [60].

Other approach for modelling the number of crossing collision candidates is calculated based on the minimum distance to collision (MDTC). A semi-axes ship domain is used for the near-collision analysis [50]. A method of Fuzzy FMEA is implemented for risk assessment in the Malacca Strait [61]. Reliability and validity of the several methods on ship-ship collision analysis was investigated by implementing 3 reliability criteria and 4 validity criteria [62].

However, the probability of ship collision in the turning area has not been investigated in the abovementioned models. In this paper, besides estimating the ship's probability of collision in the bend of the two-lane canal, that for stranding is also analyzed. The study used the MMG model for simulating the turning maneuvers. The initial conditions for maneuvering simulations were derived from the AIS data.

7.3 AIS Data

The data used in this Chapter has been presented in Section 2.3.4. The distribution of yaw rate is used in this Chapter to estimate the probability of collision.

7.4 Methods

The method of maneuvering simulation using the Maneuvering Modelling Group (MMG) has been presented in Section 3.2. The proposed method of estimation on the number of collision candidates using AIS data analysis is shown by Figure 7-2. The method is developed based on Friss-Hansen' Model and the estimation on the number of collision candidates is compared to the statistical data of and other estimation using the method introduced by Kristiansen.

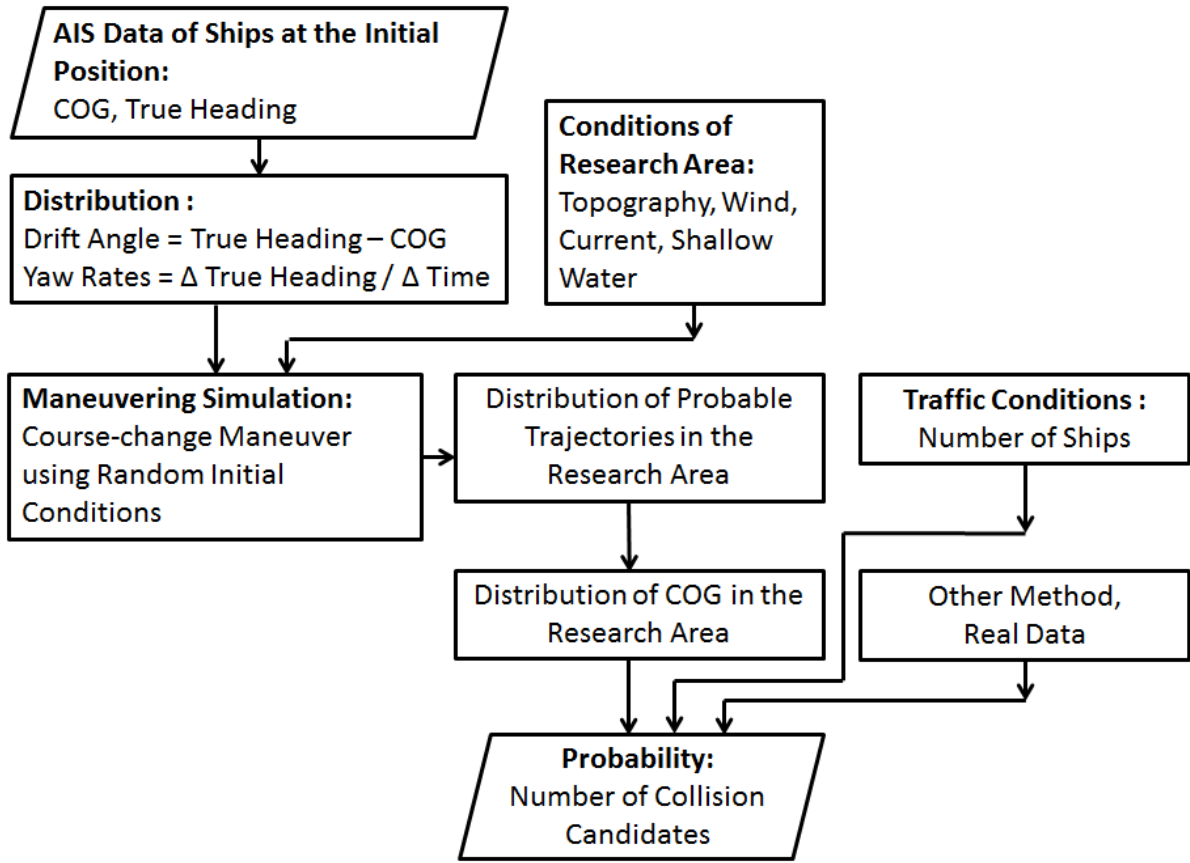


Figure 7-2 Proposed method

7.4.1 Kristiansen' Model

The head-on collision probability from the model proposed by Kristiansen is given by Equations 7-3 and 7-4, and illustrated in Figure 7-3.

$$P_a = P_i P_c \quad (7-3)$$

$$P_i = \frac{(B_1 + B_2)}{W} \frac{(v_1 + v_2)}{v_1 v_2} D N_{m1} \quad (7-4)$$

where P_a , P_c , and P_i are the probabilities of accident (collision), loss of vessel control, and collision upon the loss of vessel control (incident), respectively; W is the width of the fairway in m; D is the length of the specific section of the fairway in m; B_1 and v_1 are the beam and speed of the meeting ship, in m and m/s, respectively; B_2 and v_2 are the beam and speed of the subject ship, in m and m/s, respectively; and N_{m1} is the arrival frequency of the meeting ship in ships/s.

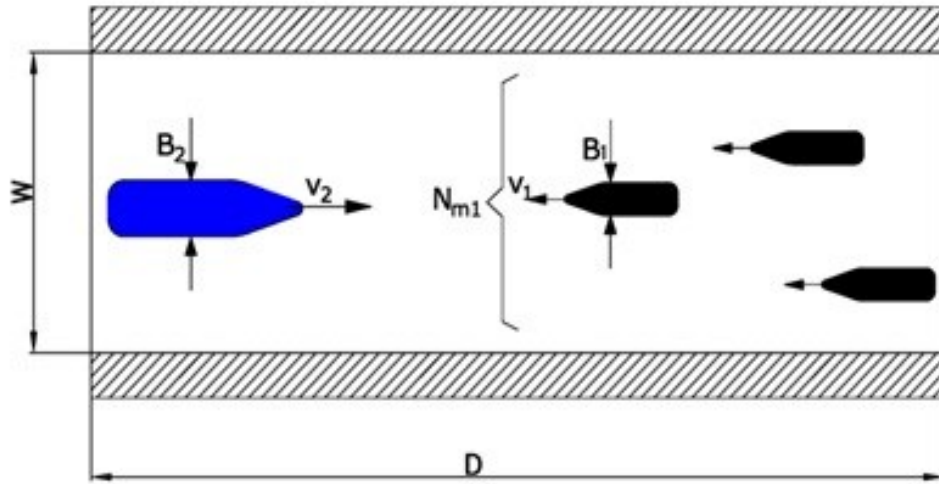


Figure 7-3 Kristiansen' head-on collision model

7.4.2 Probability of Loss Control in Madura Strait (P_C)

The model for the probability of loss control in the Madura Strait has been adopted from another researcher [52]. This probability is defined as the causation probability and calculated using the Bayesian network. The value of the probability is 1.08×10^{-4} and consists of two components, namely, steering failure and wrong action, the probabilities of which are 3.43×10^{-5} and 7.37×10^{-5} , respectively. The causation probability in the Madura Strait is higher than those in ten fairway segments in Norwegia which varied from 0.3×10^{-5} to 1.5×10^{-5} [9]. In this chapter, the probability of wrong action in the bend of the canal is investigated.

7.4.3 Friis-Hansen' Model

The Friis-Hansen' model for the number of geometric head-on collisions candidates is expressed by Equation 7-5 and Figure 7-4.

$$N_A = L_W \sum_{i,j} P_A \frac{V_{ij}}{V_i^{(1)} V_j^{(2)}} (Q_i^{(1)} Q_j^{(2)}) \quad (7-5)$$

where L_w is the length of the canal segment; P_A is the probability that two ships being in a head on meeting situation; $V_{ij} = V_i^{(1)} + V_j^{(2)}$ is the relative speed between the vessels; $Q_i^{(1)}$ and $Q_j^{(2)}$ are the number of passages per time unit for each ship type and size in each direction, (1) and (2).

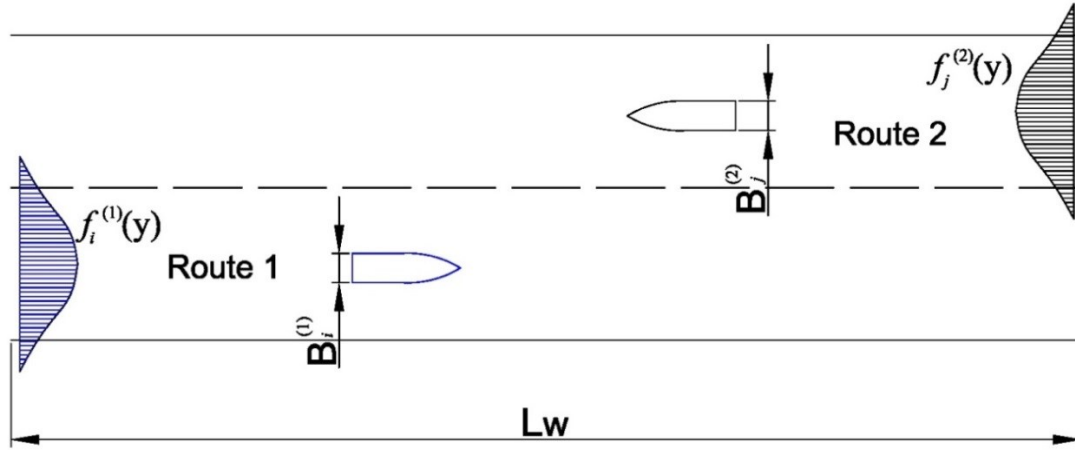


Figure 7-4 Friis-Hansen' head-on collision model

The lateral probability distribution of ships in the routes, $f_i^{(1)}(y)$ and $f_j^{(2)}(y)$, is used to estimate the probability of head on meeting situation. The probability of ships being in a head-on meeting situation in the bend of the canal is proposed in this chapter.

7.4.4 Proposed Model

The proposed model is developed based on the Friis-Hansen model [8] by proposing a method to estimate the probability of ships in meeting situation. The proposed model is also compared to the method proposed by Kristiansen [9]. The proposed collision model in the bend of the canal is presented in Figure 7-5.

Course alteration maneuver is divided to two paths, steady turn and counter rudder. The subject ship will enter the opposite lane if the ship' course when entering the zone z is less than the limit course over ground (COGlim), 153° , as shown in Figure 7-5. The probability of subject ship entering the opposite lane is estimated based on the simulation of maneuvering using the MMG model. The proposed model is expressed by Equations 7-6 to 7-10.

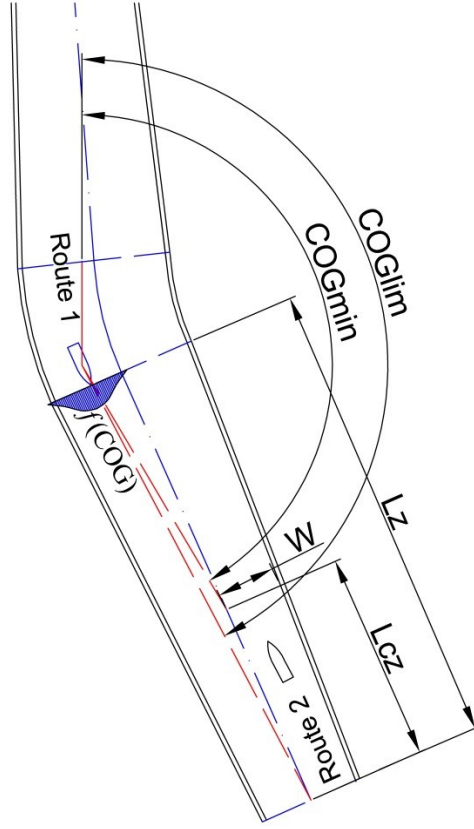


Figure 7-5 Collision probability model for the bend of two-lane canal

$$N_A = L_Z \sum_{i,j} P_{cz} \frac{V_{ij}}{V_i^{(1)} V_j^{(2)}} (Q_i^{(1)} Q_j^{(2)}) \quad (7-6)$$

$$P_{cz} = P_{olz} P_{gcz} \quad (7-7)$$

$$P_{gcz} = P_{lcz} P_{bcz} \quad (7-8)$$

$$P_{lcz} = \frac{L_{cz}}{L_Z} \quad (7-9)$$

$$P_{bcz} = \frac{B_i^{(1)} + B_j^{(2)}}{W} \quad (7-10)$$

where L_Z is the length of zone z , the transition part of the bend of the canal as shown in Figure 7-5; P_{cz} is the probability that two ships being in a head on meeting situation in the critical zone of zone z ; $V_{ij} = V_i^{(1)} + V_j^{(2)}$ is the relative speed between the vessels; $Q_i^{(1)}$ and $Q_j^{(2)}$ are the number of passages per time unit for each ship type and size in each direction in zone z , (1) and (2); P_{olz} is the probability of a ship entering the opposite lane in zone z ; P_{gcz} is

geometrical collision probability in the critical zone of zone z ; P_{lcz} is the probability of a ship being in the critical length of zone z ; P_{bcz} is the probability of a ship being in the critical distance side-by-side in zone z ; L_{cz} is the length of critical zone in zone z which depends on distribution of course over ground $f(COG)$; $B_i^{(1)}$ and $B_j^{(2)}$ are the width of each ship type and size in each direction, (1) and (2); and W is the width of lane.

7.4.5 Collision Energy Loss

Collision energy loss is considered to be the consequence of accident and is calculated as the sum of the amounts of energy released in the ξ and η directions [63], based on Equations 7-11 and 7-12 for a sticking case.

$$E_{\xi} = \frac{1}{2} \frac{1}{D_{\xi} + \mu D_{\eta}} \dot{\xi}(0)^2 \quad (7-11)$$

$$E_{\eta} = \frac{1}{2} \frac{1}{\frac{1}{\mu} K_{\xi} + K_{\eta}} \dot{\eta}(0)^2 \quad (7-12)$$

where ξ and η are normals to the impact surface as shown in Figure 7-6; $\dot{\xi}(0)$ and $\dot{\eta}(0)$ are the relative velocities of ships; D_{ξ} , D_{η} , K_{ξ} , and K_{η} are constants calculated through correlation between the relative acceleration and forces; and μ is the ratio of impact impulses [63].

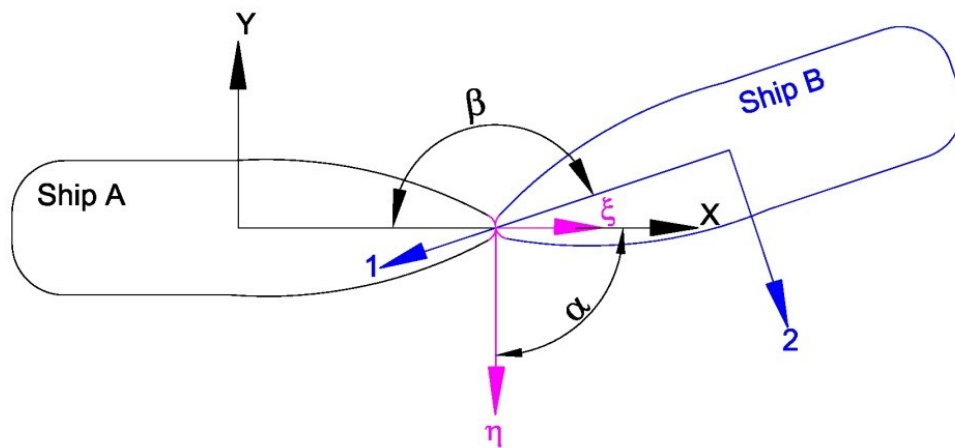


Figure 7-6 Coordinate system of ship-ship collisions

7.5 Results

7.5.1 Normal Course Alteration Maneuver at the Bend of Canal

The course alteration maneuver of the subject ship at the bend of the canal was simulated, and Figure 7-7 shows its trajectory during this operation. The speed of the ship is 10 kts with rudder angle series as shown by blue line in Figure 7-8. The course series of the ship is presented by red line in Figure 7-8.

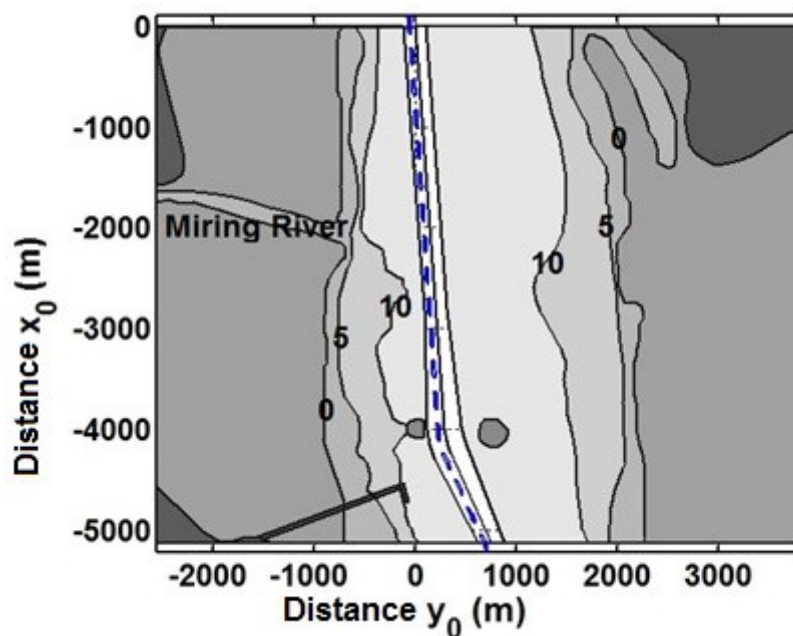


Figure 7-7 Normal path of subject ship

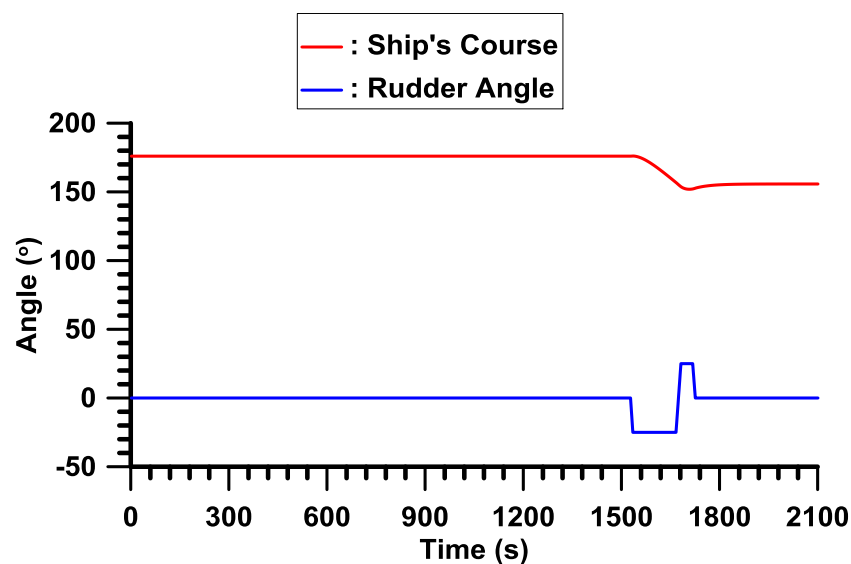


Figure 7-8 Time series of ship's course and rudder angle

7.5.2 Probability of Wrong Maneuver at Bend of Canal

The turning maneuver at the bend of the canal was expressed using fixed initial drift angle and random initial yaw rate given by Equations 13–15.

$$u_{0i} = (10 \times 0.514) \cdot \cos(-0.01008) \quad (7-13)$$

$$v_{0i} = (10 \times 0.514) \cdot \sin(-0.01008) \quad (7-14)$$

$$r_{0i} = -0.000068667 + 0.0005763 \cdot \text{randn}(1) \quad (7-15)$$

where $\text{randn}(1)$ represents the normal distribution of random numbers; u_{0i} , v_{0i} , and r_{0i} are the initials of surging, swaying and yawing speeds based on drift angle and yaw rate distributions (presented in Table 2-7).

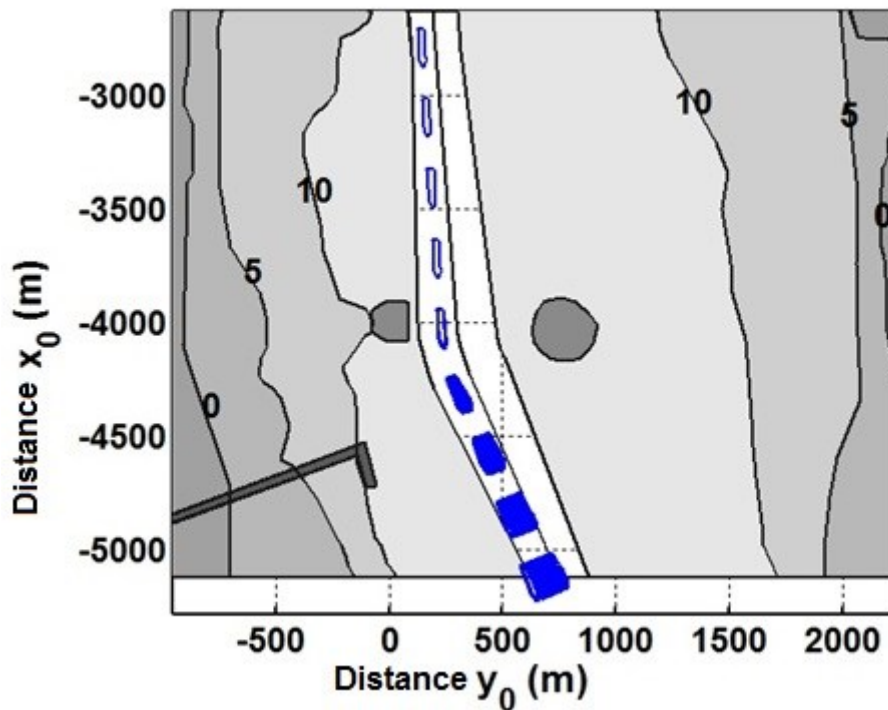


Figure 7-9 Probable trajectories of the subject ship

The subject ship is simulated at the velocity of 10 kts. The random initial speeds are treated on the MMG model based on Equations 7-13 to 7-15 in order to predict the trajectory. The probabilities of wrong turning maneuver leading to collision and stranding accidents were calculated based on the number of paths with courses less than 153° and larger than 159° , respectively.

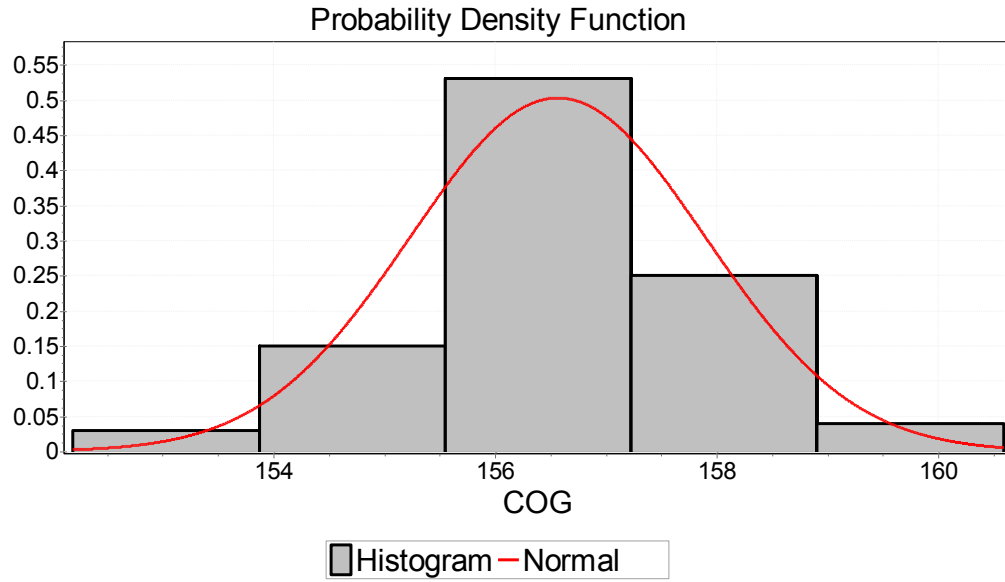


Figure 7-10 Probability density function of COG

The probable trajectories of the subject ship are shown by Figure 7-9. The probability density function of COG in the transition part of the bend of the canal is shown in Figures 7-10. The distribution of COG at the zone fits to normal distribution with mean, $\mu = 156.56^\circ$ and standard distribution, $\sigma = 1.33^\circ$. The probable trajectories show that 3% of the trajectories enter the opposite lane and 1% hit the wall of the canal. The length the transition part L_z , and the length of critical zone L_{cz} , are about 1180 m and 400 m, respectively.

7.5.3 Number of Collision

The AIS data show that the average beam (B) of ships voyaging in the strait is 18.69 m and the average number of leaving ships per day is 42. The length of the transition of the bend (L_z), width of the lane (W), and ship speed (V) are 1180 m, 100 m, and 10.642 kts, respectively. The proposed method to estimate the number of collision candidates expressed by Equation 7-6 is implemented based on the data. The comparison on the number of collision per year in zone z , using the proposed method and the Kristiansen' model is show in Table 7-1.

Table 7-1 shows a significant difference on the estimations of number of collision per year for ships sailing in zone z between Kristiansen model and the proposed method. The

Table 7-1 Estimation number of collision in zone z

Variables	Kristiansen model	Proposed method based on Friis-Hansen' model
Probability of steering failure in Madura Strait, P_{sf}	3.43×10^{-5}	3.43×10^{-5}
Probability of wrong action, P_{wa}	0.0300	0.0300
Causation probability, $P_c = P_{sf} + P_{wa}$	0.0300343	0.0300343
Average number of entering or leaving ships per year, $Q_i^{(1)}$, $Q_j^{(2)}$, N_{m1}	15,330	15,330
Probability of collision upon loss of vessel control, P_i	0.0783	-
Probability of collision per passage, P_a	0.0023	-
Probability that two ships being in a head on meeting situation, P_{cz}	-	0.0038
Number of collision candidates per year, N_A	-	12.2115
Estimation number of collision per year, N_{coll}	36.0680	0.3668

number of collision estimated using Kristiansen model is about 100 times higher than that resulted from the proposed method because the geometric equation of Kristiansen shown in Equation 7-4 does not consider the probability of two ships in meeting situation P_{CZ} , as shown in Equation 7-6, which not only depends on the width of ships and lane but also the critical length L_{CZ} and the probability of ship entering the opposite lane P_{Olz} . In this case the Kristiansen' model calculates the geometric probability by assuming that the ship has already loss of control in zone z using the causation probability P_c . On the other hand, the proposed method based on Friis-Hansen' model, firstly the geometric probability to estimate the number of collision candidates is calculated then the probability of ship failing to avoid collision P_c , is considered.

The annual number of collision in the Madura Strait taken from the Port Authority of Tanjung Perak is presented in Figure 7-11. The average actual number of collision in the

Madura Strait which has about 20 km length is 11 collisions per year. The average number is about 0.55 collisions per 1000 m of fairway length, annually. The estimation of annual number of collision in zone z with 1180 m length is 0.3668. The estimation number is about 0.3108 collisions per 1000 m length of canal per year and the estimation number to the real number ratio is 0.56.

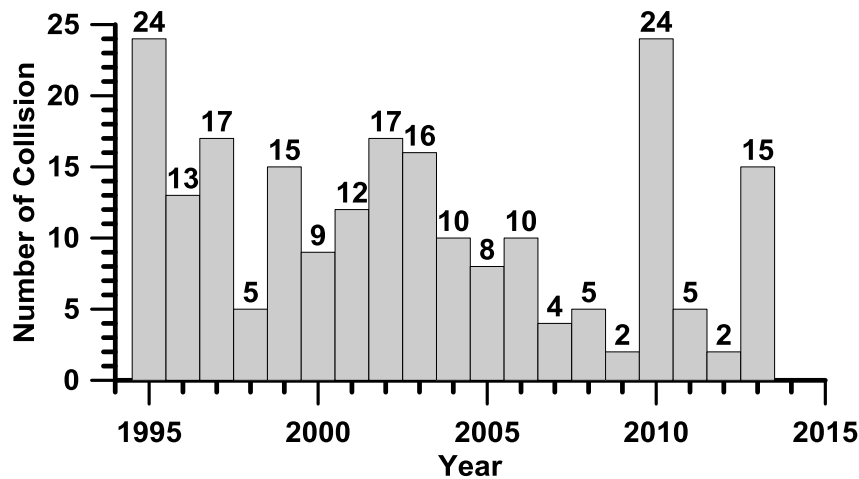


Figure 7-11 Annual number of collision in Madura Strait [64]

7.5.4 Risk Estimation

Total energy loss of head head-on collision by angle between the center lines of two ships is calculated according to Equations 7-11 and 7-12 and presented by Figure 7-12. The energy is calculated based on the ships' speed of 10 knots and the position of surface contact is at the bow of the ships, $\alpha = 90^\circ$.

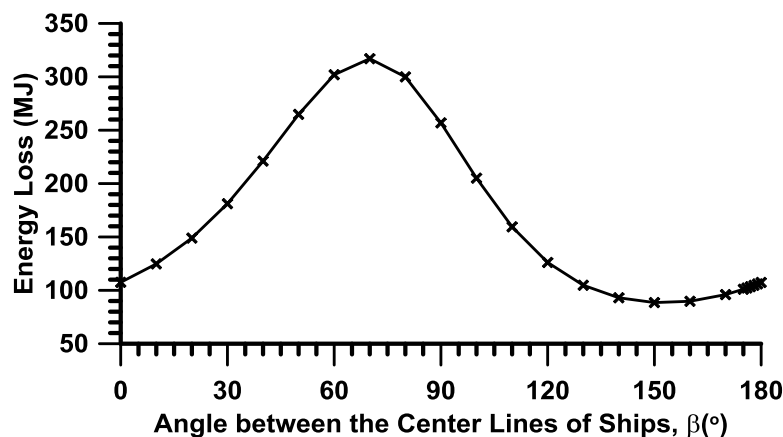


Figure 7-12 Energy loss of head-on collision

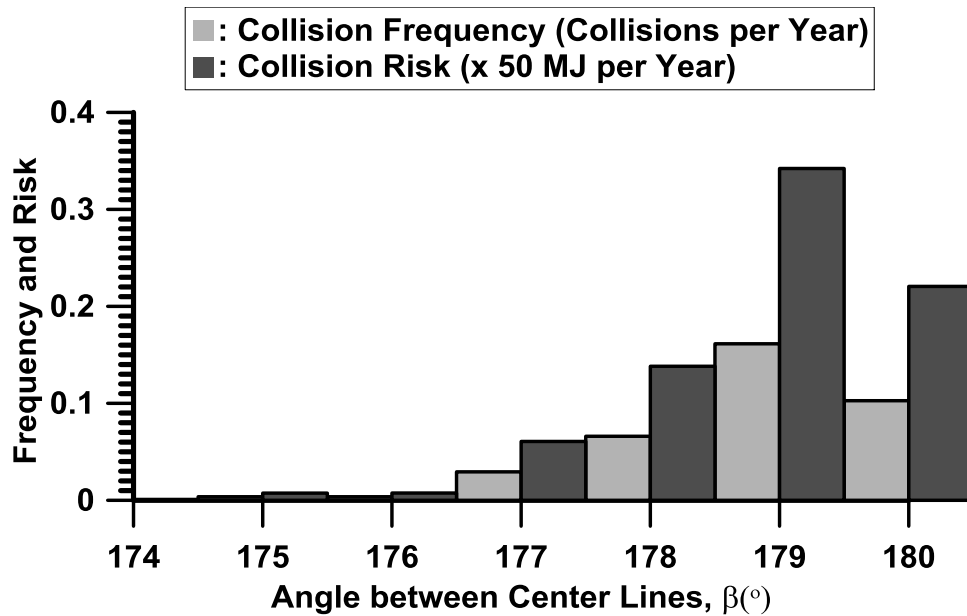


Figure 7-13 Estimated frequency and risk in the zone z by β

The number of collision per year by the angle between center lines of ships is shown by Figure 7-13. The angle is calculated based on the distribution of COG of entering ships as shown in Figure 7-9 and the normal course of leaving ship in zone z .

Collision risk is calculated from the collision frequency multiplied by the energy loss and the result is shown by Figure 7-13. Acceptance criteria of collision risk based on the energy loss have not been formalized yet. However, Kristiansen [45] considers that the energy which is more than 50MJ is a high-impact energy accident. Figure 7-13 shows the collision risk is not high-impact energy accident. The energy will be high if the angle between the center lines of the ships are about 45° to 90° as shown in Figure 7-12.

7.6 Discussions

The estimation of collision frequency using the proposed method based on the Friis-Hansen' model is considered to be reasonably agreement because the ratio between the estimation and the real frequency is more than 0.2 (ratio value ≥ 0.2). However, the estimated frequency using Kristiansen' model is overestimated which is about 56 times the actual number of collisions. In this case, the calculation on the estimation of the probability of loss of vessel control is calculated based on the probability of steering failure and the probability of wrong action. It seems that the probability of wrong action in the bend of the

canal estimated using the MMG model is not proper to be implemented in this method because the geometric probability, the probability of collision upon the loss of vessel control, P_i , does not considered the critical length L_{cz} and the probability of ship entering the opposite lane $Polz$.

Accordingly, in the method of Kristiansen, the probability of loss of vessel control should be calculated based on the average probabilities of probability of steering failure and probability of wrong action in the Madura Strait which are 3.43×10^{-5} and 7.37×10^{-5} , respectively [52]. By using these probabilities, the collision frequency in the transition part of bend of the canal is 0.13 collisions per year and the ratio value is 0.23.

The probabilities of angles between the center lines of ships taking head-on collision in the zone z are estimated from distribution of ships' courses in the zone using the maneuvering simulation. The angles are from 175° to 180° and total risk per year in the zone is considered to be low about 39 MJ (≤ 50 MJ). However, the length of the zone is just about 6% of the length of Madura Strait and the total collision risk in entire length of Madura Strait is considered to be high-impact energy accidents.

7.7 Conclusions

The AIS data and MMG model were used to develop a model for determining the probability of collision in the canal of the Madura Strait. The consequence of the accident was calculated as energy losses. Some conclusions were obtained from the implementation of the proposed method for estimating the probability of wrong turning maneuver in the research area, as follows.

1. The probability of collision upon the loss of vessel control in the canal is 0.078.
2. The Kristiansen model can be implemented in the bend of the canal but the wrong action estimated in the bend using the maneuvering simulation cannot be applied. The estimation of wrong action in the Madura Strait calculated by other researcher using the Bayesian network is properly implemented for this method and the ratio value is 0.23. The frequency in the zone using this method is only 0.1297 collisions per year.

3. A new method for estimating the probability of wrong turning maneuver is introduced based on the MMG model using distributions of drift angle and yaw rate calculated from AIS data.
4. The proposed method based on the Friis-Hansen' model is appropriate to be applied to estimate collision frequency in bend area of canal with ratio value, the ratio between estimation and actual collision frequency, of 0.56. The frequency of collision in the transition part of bend of the canal is 0.3668 collisions per year.
5. The total collision risk in the new two-lane canal is considered to be high-impact energy collisions (≥ 50 MJ per year).

Chapter 8

Discussions and Conclusions

8.1 Discussions

The development of navigation safety analysis for developing port area using maneuvering simulation and AIS data in the Madura Strait has been performed. The methods of ship barrier and collision avoidance, navigation safety-indices, and collision probability as well as collision risk have been proposed. The suggestions in the attempt to prevent the collision accident in the research area have been proposed, including the movement of center of the passage and the proposed maximum safety speed in the research area. The proposed route for ship to leave the new port and optimum route for ship to enter the existing port have also been recommended.

However, the proposed route has not yet considered an optimal position of anchorage zones. The analysis of optimum anchorage positions may improve the navigation safety in the port area. In addition, analysis of collision risk using MMG model and AIS data in the new canal of the Strait has also been investigated. Other analysis, including the evacuation assessment of the accident may need to be carried out in the future. The analysis is essential to minimize other consequences of the accident. Discussions regarding the study are presented as following.

1. Implementation of the Methods in Other Developing Ports Area

In this study, the navigation safety analysis was conducted by taking a case study in the developing port area of Tanjung Perak Port in the Madura Strait. Simulation of the

subject ship in the area was carried out using a map developed in MATLAB program. The data of coordinate of port topography was transferred from the port map into the map of MATLAB program. The methods of navigation safety analysis were developed to be implemented in all of developing ports, especially in the main sea-corridors of Indonesia. The first stage of the development of Tanjung Perak in Lamong Bay has been established. The port has been officially operated since May 22, 2015 by the President of Republic of Indonesian. The port is declared as the most modern and environmentally friendly in Indonesia. The development of other main sea-corridors including Port of New Tanjung Priok in Jakarta, Port of Kuala Tanjung in Belawan, Port of Makasar in Sulawesi and Port of Sorong in Papua are still in progress.

The implementation of the methodology in other ports of the main sea-corridors of Indonesia will needs a lot of work to transfer the coordinate data of the port maps into the MATLAB program. Another method needs to be taken in order to increase the efficiency of the work. In the future, the coordinate of maneuvering simulation will be transfered into the geographic information system (GIS).

2. AIS Data Analysis for Initial Conditions of Ship Maneuvering in the Research Area

The analysis of initial ship conditions for maneuvering derived from AIS data is one of the important parts of this study. In this study, some initial conditions are analyzed from the AIS. Initials of ships speed, yaw rate, drift angle, and rudder angle are predicted using several methods based on the AIS data including, speed over ground (SOG), latitude, longitude, course over ground (COG), and true heading. The initial of yaw rate provided the most significant effect to the distribution of probable trajectories.

Three methods were applied for the analysis of yaw rate distribution in the research areas. Firstly, in the beginning step of the research which are applied in Chapter 4 and Chapter 7, the yaw rate was calculated based on the difference between the recorded data of true headings from the AIS data. This method shows low accuracy because the AIS data were recorded periodically in about 10 to 20 s.

Second, in the medium step of the research which is applied in Chapter 5, the method was improved by using small zigzag maneuvers as the presentation of the course keeping maneuver on a straight trajectory before taking a course-change

maneuver. The time series of yaw angle derived from the AIS data is compared to those of small zigzag maneuvers. The yaw rate distribution in the research area is determined based on the maneuver simulation which has yaw angle time series alike with that from AIS data.

Third, in the last step of the research the method was improved again. The improved method was applied in Chapter 6. In this case, the distribution of yaw rate is also determined based on the maneuvering simulation. The method to determine the distribution of yaw rate is not only based on the similarity of yaw angle time series but also the trajectories between the simulation and the AIS data.

In the future the last method is considered as the most accurate which will be implemented in other areas of developing ports. This method is not only more accurate than other methods, but also more effective because this method covers larger area which is then divided into several paths of the research area.

3. Maneuvering Simulation for Other Types and Classes of Ships

The maneuvering simulation using the maneuvering modelling group (MMG) model was implemented for a subject ship in the research area. The subject ship was chosen based on the biggest dimension of vessel voyaging in the research area. In addition the ship type is determined based on the largest area of ship above the water line which is the most sensitive to the effect of wind disturbance.

In the future, to improve the analysis of navigational safety in the research area, other types and classes of ships voyaging in the research area needs to be implemented for the maneuvering simulation. The dimension of ship and type will affect the barrier of ships, probability of collision, and the estimation of collision risk.

4. Ship Barrier in the New Port Area of Lamong Bay

The dimension of ship barrier in the area of new port was estimated based on the distribution of initial yaw rate when taking course-change maneuver. The width of ship domain was determined according to probable trajectories simulated using MMG model. The method has been published in the Journal of Marine Engineering Frontiers. The width of the ship domain resulted from the method was less than the width of Fujii' ship

domain [5]. However, the distance from the ship barrier to the structure of the new port is less than that proposed by Inoue [6]. Accordingly, the center of fairway in the area is suggested to be moved about $0.12L$ of the subject ship away from the new port.

The method used for the determination of distribution of initial yaw rate of entering ships when taking course alteration is the first method. In the future the width of ship barrier in the developing port area will be determined by using the latest method. The barrier of leaving ship in the new port area also needs to be conducted for the future work. The movement of the position of the anchorage area will be analyzed based on the barrier of the leaving ship.

The separation of the fairway for the new port from the fairway for the existing port is also the other part of the future work. Trajectory 2 presented in Figure 4-10 shows that the leaving ship of the new port cross the entering fairway of the existing port which is also considered as the new danger area. The separation of the fairway of the ports is suggested as the measure to avoid collision in the new danger area. New buoys are suggested to be installed in every bend of the fairway. A scheme of the fairway separation is recommended as shown by Figure 8-1. Red and green triangle show suggested new buoy positions.

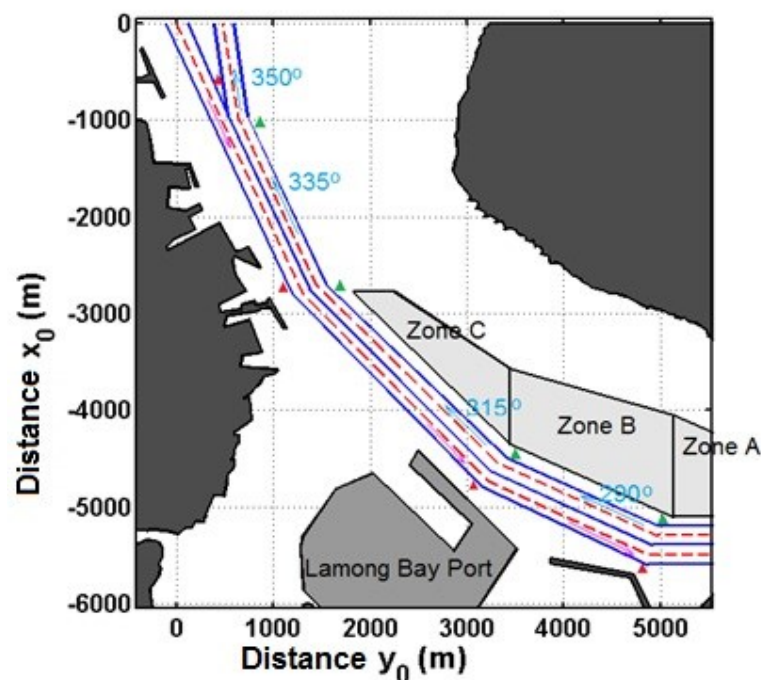


Figure 8-1 Separation scheme of the fairways

5. Evaluation of the Optimal Trajectory in the Research Area

Development of navigation safety-index method to determine the optimal safe trajectory has been performed. The method has been submitted for publication in the Journal of Maritime Affairs. The optimal trajectory is selected from probable trajectories simulated based on the distribution of initial yaw rate when entering the research area. In this method the distribution of yaw rate is estimated based on the small zigzag maneuver in a straight trajectory before entering the research area. The method was implemented in the area located between the anchorage zones representing the existing condition of the port area.

In the future, the distribution of yaw rate will be determined based on the last method which does not only consider the time series of yaw angle but also the time series of ship position. The evaluation of the optimal trajectory in the area will also need to be considered other conditions including the position of new port, the position of new anchorage zones, and the separation of the fairway for the new port and the existing port.

Furthermore, in the method emergency level (EL) and distance level (DL), the stopping distance of the subject ship was estimated using IMO equation. The implementation of stopping maneuver to estimate the stopping distance will be considered in the future work.

6. Probability of Ships on Collision Courses when Using Astern Maneuvers

Taking a crash astern maneuver is one of choices decided by navigator to avoid collision with other ships losing control due to steering failure or wrong action. The lateral deviation of stopping position from the intended position has been simulated based on the effect of reversing propeller to the lateral force and yaw moment. The maximum speed of ship in the area of new port has been suggested to avoid excessive lateral deviation and collide with the structure of the new port. This analysis is developed based on the paper published in the Journal of Marine Navigation and Safety of Sea Transportation.

The distribution of lateral deviation was estimated based on the concept of potential area of water (PAW) for maneuvering. Originally, the concept of PAW proposed by Inoue is developed based on some positions when the maneuver is ordered. In this new

PAW, besides the positions of the maneuver, the distribution of initial yaw rate is also considered. The improved method to determine the distribution of yaw rate has been implemented in this analysis. Accordingly, the method can be applied in other developing ports. In this study, the probability of taking a crash astern maneuver has not yet been discussed. In the future it should be investigated to estimate probability of the collision based on the AIS data.

7. Collision Risk Estimation in the New Two-lane Canal

Collision risk is estimated based on the estimation of collision probability and its consequence in term of energy losses. A method to estimate number of collision was proposed. The proposed method was developed based on the Friss-Hansen' method [8]. The probability of ship entering the opposite lane was estimated based on probable trajectories using maneuvering simulation. The analysis was developed based on a contribution in OMAE Conference 2014. In this analysis the probable trajectories were simulated based on yaw rate distribution determined using the first method. In the future last method is considered to be implemented. New buoys are also recommended to be installed in the bends of the canals as shown by Figure 8-2.

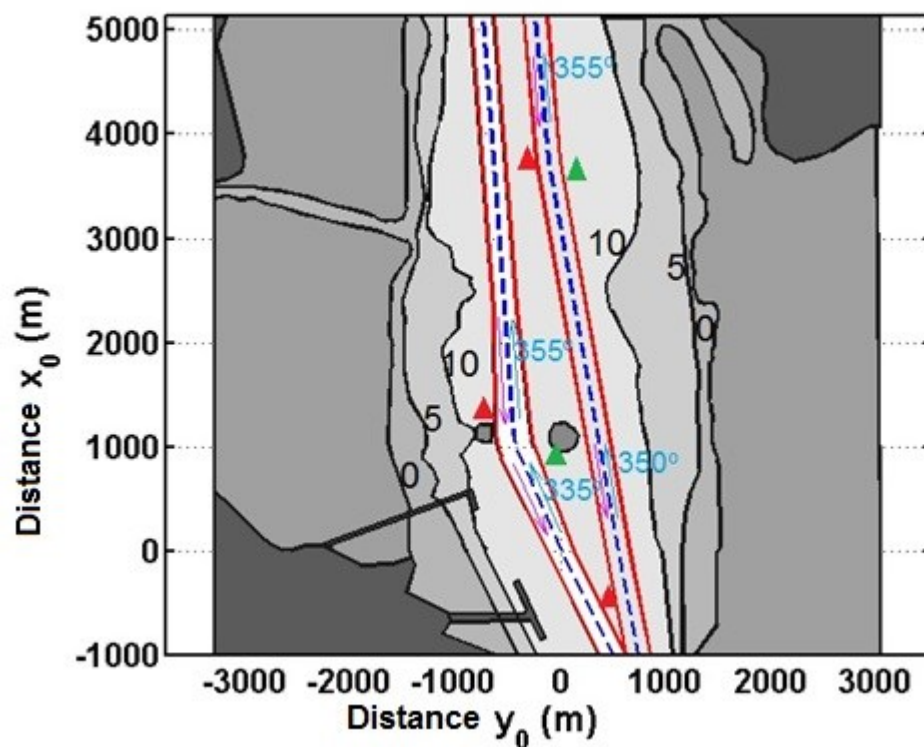


Figure 8-2 New buoys in the bend of the new canal

8.2 Conclusions

The method of navigation safety analysis using maneuvering simulation and AIS data in the Madura Strait has been developed. The maneuvering simulation program of the MMG model was developed using MATLAB program. The MMG model considers the condition of shallow water and the disturbances of wind and current. In Chapter 4, drift angle and yaw rate of an entering ship are analyzed from the COG and true heading using interpolation method and treated in the MMG model to identify and estimate the width of danger area. In Chapter 5, the distribution of yaw rate is analyzed from the trend of yaw angle of a small zigzag maneuver. The trend of yaw angle is compared to the trend of true heading of a ship from AIS data. The distribution is treated as the initial condition of turning maneuver using the MMG model to estimate possible trajectories and determine the optimal route. A new method of navigation safety-index is proposed to determine the optimal route. In Chapter 6, the trend of true heading and SOG as well as the trajectory from AIS data are used as the reference for the subject ship to be followed using the maneuvering simulation. The distribution of yaw rate is estimated from the simulation. The distribution is treated in the simulation of crash astern maneuvers to estimate the probability of ship on collision course.

Simulation of ship maneuvering to estimate the width of ship barrier in order to avoid ship-ship collision was developed based on the identified danger area and is presented in Chapter 4. In this chapter, a subject ship exiting a new port in the Madura Strait is simulated to avoid collision with a target ship entering the Tanjung Perak Port area. The danger area of target ship entering the port area is treated as ship domain, and ship barrier. Ship domain is defined as the free area surrounding a ship to avoid collision. The result of the method is compared to other method. The safest route of subject ship is determined using trial maneuver considering the safety index of emergency level (EL).

The analysis of ship domain and danger area as well as the evaluation of passage position and the new port position have been performed. The analysis was developed by using maneuvering simulation based on distribution of AIS data. The location of danger area and the width of ship domain in the shallow water of the port area were predicted by randomizing the initial conditions of entering ship taking course alteration maneuver at the bend of the passage. The danger area of the entering ship was identified as obstacle which has

to be avoided by subject ship exiting the port. The simulation confirms that some of the possible trajectories of target ship were on collision courses with ships anchoring in the anchorage zones.

The simulation also showed that avoiding the danger area of anchorage zone will create another danger area in the new port area. The dimension of the danger area is used as the dimension of ship domain which should be free of other ships for avoiding ship-ship collision. Conclusions from Chapter 4 are follows:

1. The width of ship domain in port area estimated based on the danger area was about $1.12L$ which is less than that calculated based on Fujii's method, $1.6L$ [5].
2. The width of free space between the danger area and port structure was $0.56L$ and the distance between the passage and anchoring ship was $0.5L$. The distances were less than requirement introduced by Inoue [6] which are $0.68L$ and $0.89L$ respectively.
3. Furthermore, the route of the exiting ship is determined in order to avoid collision with entering ship in the danger area. The route is determined based on the evaluation of navigation safety which is measured using the method of emergency level (EL).

A proposed method for the assessment of navigational safety using MMG model and AIS data was explained in Chapter 5. The method was developed based on Emergency Level (EL) and Environment Stress (ES) methods. The proposed method is intended for seeking the optimal of safety route for developing port area. As a case study, the method is implemented in the existing condition of the passage located between anchorage zones of the port area. The change of route and position of navigation aids can be determined for the developing port area based on result of the method. The EL and ES of subject ship entering the port area between the anchorage zones had been evaluated according to the existing condition of the developing port area. The boundary lines of anchorage zones and shallow water of the coast are treated as virtual environment obstacle lines, besides the structure of port jetty. The waterlines of ships anchoring out of the anchorage areas are the representation of traffic obstacle of ship maneuvering in the area. A new method of navigational safety assessment method was introduced in Chapter 5. The method was developed based on the existing method of the emergency level (EL) and environment stress (ES). The existing methods were not able to seek the optimal route. Conclusions from Chapter 6 are listed as following.

1. The new methods of distance level (DL), aggregate distance level (AgDL) and average distance level (AvDL) were introduced in order to determine an optimal route in the developing port area.
2. Firstly, distributions of drift angle and yaw rate on a straight passage before taking a turning maneuver were analyzed.
3. The distribution of drift angle on the passage was analyzed from AIS data of ships belong to the same class with a subject ship.
4. However the yaw rate distribution of ship on the area was predicted using small zigzag simulation because the yaw rate data is not available in AIS data.
5. The yaw angle time series of subject ship resulted from the simulation was compared to the true heading of ship from AIS data.
6. The distributions were treated in the maneuvering simulation to estimate possible trajectories.
7. The navigational safety indices of all possible trajectories were calculated based on the distances to obstacles and the stopping distances.
8. The stopping distance is calculated based on an estimation equation from IMO.
9. The AvDL of the normal trajectory was 0.2.
10. The proposed method found suggested the optimum trajectory with the AvDL of 0.39.

In the Chapter 6, development of collision candidate frequency method using MMG model and AIS data has been analyzed and discussed. The method is developed for predicting the probability of ship on collision course upon taking crash astern maneuvers. Potential trajectories of crash astern maneuvers are predicted based on distributions of initial conditions disturbances for the maneuver. A new potential area of water (PAW) for maneuvering was introduced in Chapter 6. Crash astern maneuvers with uncertain initial condition of yaw rate were treated to develop the new PAW. Probability of ship on collision courses upon taking crash astern maneuvers was estimated using the new PAW. The normal entering trajectory of ship was plotted based on AIS data. A subject ship was simulated using MMG model to take the same trajectory and yaw angle trend with the AIS data. The yaw rate time series of ship on the trajectory was taken from the MMG model. The conclusions from Chapter 6 are follows:

1. The trajectory was divided into 6 areas including 3 areas of course keeping and 3 areas of course changing.

2. Crash astern maneuvers including slow crash astern, half crash astern and full crash astern were taken at 4 initial positions for each area.
3. The simulation confirmed that the maximum safety speed of ship in the research area of port area in the Madura Strait is 6 knots.
4. Based on the distribution of ship speed in the area derived from AIS data, it is estimated that the probability of ships on collision courses upon taking a slow crash astern maneuver is 50%.
5. The largest lateral deviation was found at area D, area of long turning located in front of the position of new Lamong Bay Port. The distribution of lateral deviation at the area fits with normal distribution with the mean of -5.894B and standard deviation of 0.342B. The large distribution of lateral deviation in this area is in line with to distribution of yaw rate in the area.

The collision risk analysis in the bend of the new canal has been discussed in Chapter 7. A method to estimate the probability of collision in the bend of the canal was proposed. The conclusions from Chapter 7 are follows:

1. The probability of collision upon the loss of vessel control in the canal is 0.078.
2. A new method for estimating the probability of wrong turning maneuver is introduced based on the MMG model using distributions of drift angle and yaw rate calculated from AIS data.
3. The proposed method based on the Friis-Hansen' model [8] is appropriate to be applied to estimate collision frequency in bend area of canal with ratio value, the ratio between estimation and actual collision frequency, of 0.56. The frequency of collision in the transition part of bend of the canal is 0.3668 collisions per year.
4. The Kristiansen model [9] can be implemented in the bend of the canal but the wrong action estimated in the bend using the maneuvering simulation cannot be applied. The estimation of wrong action in the Madura Strait calculated by other researcher using the Bayesian network properly implemented for this method and the ratio value is 0.23. The frequency in the zone using this method is only 0.1297 collisions per year.
5. The total collision risk in the new-two-lane canal is considered to be high-impact energy collisions (≥ 50 MJ per year).

8.3 Further Researches

The development of navigation safety analysis for developing port area had been performed. Several further researches need to be conducted in order to improve navigational safety in a developing port area. The further researches are as follows:

1. The distribution of yaw rate in the research area has been analyzed using 3 different methods. In the future, the method will be developed by using more AIS data to improve the goodness of fit of the data to a distribution and to cover AIS data in 2 seasons, West Monsoon (rainy season) and East Monsoon (dry season).
2. Evaluation on the effect of Monsoon seasons to navigational safety using the MMG model and AIS data.
3. The implementation of the navigation safety analysis methods in other developing port areas, i.e. the ports in Belawan, Jakarta, Makasar, and Sorong.
4. The method of probability of ships on collision courses upon taking astern maneuvers has been developed. In the future, probability of ship taking astern maneuvers will be investigated using AIS data.
5. Evaluation on the optimum position of anchorage zones in the developing port area by considering the probability of collision in the area.
6. The analysis on the optimum route of entering and leaving trajectories considering the simulation of anchorage zone positions.
7. Collision risk in the new canal has been estimated based on distribution of yaw rate of ships using AIS data in the latitude position of the bend of the canal. In the future, after the canal will be operated, the reliability of the distribution will be improved using the data in the real position.
8. Analysis of navigational safety in a strong wind, such as the tropical cyclone and any type of local winds will be carried out in the future by using the MMG model and AIS data.
9. The assessment on the evacuation of ship collision and other accidents using maneuvering simulation and AIS data.

The navigation safety analysis is intended to propose new navigational aids and measures for collision avoidance. In the future, the variables of the analysis should also include human factors and management, such as knowledge and skill, and experience of navigators, and crew management in the research area.

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