Collision Risk Analysis and Oil Spill Dispersion Modelling in Lombok Strait

A A B Dinariyana¹, M A Avesina¹, K Sambodho²,³, F Fahrirozan³
¹Department of Marine Engineering, Institut Teknologi Sepuluh Nopember (ITS) Surabaya
²Department of Ocean Engineering, Institut Teknologi Sepuluh Nopember (ITS) Surabaya
³Center of Excellence in Maritime Safety and Marine Installation (PUI-KEKAL), ITS Surabaya

e-mail: kojex@its.ac.id

Abstract. Lombok Strait is one of the water areas that designated for international shipping lanes since it has been adopted as the Indonesia Archipelagic Sea lane (IASL) II in 1998. Foreign-flagged ships passing through the strait from southbound to northbound and vice versa. Along with being an archipelagic sea lane, the strait also occupied by high-density crossing traffic connecting Bali and Lombok islands. This crossing traffic mainly dominated by passenger ferry Ro-Ro and pleasure ships as both Bali and Lombok islands are well known as tourist destinations. Aside from being a tourist destination, several islands around the Lombok Strait are also dedicated to Marine Protected Areas (MPA). There are two areas designated for MPA by the Indonesian government in the vicinity of Lombok Strait; Nusa Penida on the west side of IASL II and Gili Matra on the east side. The traffic condition allows the potential for collisions on ships passing through and crossing the Lombok Strait which is very likely caused by navigation errors, human errors, weather conditions, and other technical problems. This study aims to determine the collision risk analysis in terms of annual frequency of collision and grounding as well as the potential dispersion of oil that occurs in the event of a ship collision near the MPA of Nusa Penida. Based on one-year traffic data and forecasted to 20 years, collision and grounding frequencies analysis was conducted using iWRAP method. The analysis found that annual frequency including head-on, overtaking, crossing, merging, bend, and grounding is 4.73x10⁻¹. In addition to the frequency of collisions, oil spill dispersion simulations were carried out using GNOME under two different conditions wind and sea current directions; wind and sea currents that heading to the Northwest, and Southwest. Given a scenario of collision occurred close to Nusa Penida island involving tanker ship that resulting hull damage and oil spill while the wind and sea current directed to Southwest, simulation resulting that oil spill will disperse and polluting MPA of Nusa Penida.

1. Introduction
Indonesia is a country located in the world's sea transportation routes. This resulted in many foreign-flagged ships passing through Indonesian waters. One of the waters designated for international shipping lanes is Lombok strait. This strait has been used as a primary route since it has been adopted as the Indonesia Archipelagic Sea Lane (IASL) II in 1998[1]. The ships exercising and voyages the right of IASL II through the strait from southbound to northbound and vice versa. Along with the
existence of archipelagic sea lane, there is also a high-density crossing traffic line oscillate Bali and Lombok islands that cuts the strait. This crossing traffic mainly occupied by passenger ferry Ro-Ro and pleasure ships as both Bali and Lombok Islands are well known as tourist destinations. The density and routes condition in this strait is given in Figure 1 and Figure 2.

![Figure 1. Traffic density heat map in IASL II](image1)

![Figure 2. Traffic through and crossing IASL II](image2)

This traffic condition allows the potential for collisions on ships passing through and crossing the Lombok Strait which is very likely caused by navigation errors, human errors, weather conditions, and other technical problems. One of the conditions that can occur as a result of a collision and grounding is an oil spill caused by damage to the hull of the ship. One case of ship accident occurred on July 17th, 2014, KMP. Gelis Rauh, a ferry ro-ro ship was on fire in the Lombok Strait while sailing from the Port of Padangbai in Bali to the Lembar Port in Lombok. The ship was drifted to the southward around the water area of Nusa Penida. Even though the ship accident did not result in an oil spill, the potential for the accident still can occur and endangered the existing biodiversity. Based on these considerations, this study aims to determine the potential for collisions and grounding as well as the potential dispersion of oil that occurs in the event of a ship collision near the MPA of Nusa Penida.

The annual frequency of collisions is analyzed using iWRAP method that consider several types of collision such as head-on, overtaking, crossing, merging, bend, and grounding collisions. iWRAP allows using Automatic Identification System (AIS) data to access the geometric collision candidates for several types of collision. To obtain the probability of collision, an integrated calculation can be performed since it has several causation factors values and ship domain. GNOME is used to estimate oil spill distribution when the collision occurred close to the MPA of Nusa Penida. The results of the study are expected to help the local authorities, both the guide and the port, to manage the shipping lanes in the Lombok Strait to be better, so that the potential for collisions and grounding can be reduced. Besides, oil dispersion simulation will help the authority in providing mitigation strategies to avoid the oil spill to MPA of Nusa Penida.

2. Ship collision frequency analysis
The collision between two moving vessels can pose a danger to the safety of crews, environmental damage, and losses due to damage to cargo carried by ship [3]. There are several types of ship collisions including head-on, crossing, and overtaking which are shown in Figure 3. The events involving two ships are affected by the width of the sea lane and the direction of the two ships. The impact is influenced by the speed \( V \), length \( L \), and breadth \( B \). In addition to these three types of collisions, the annual frequency of collisions is also obtained by considering the condition of merging collisions where collisions occur in the shipping lane that allows the ship to meet at one point before sailing in the same direction. Bend collision where collisions occur in cornering is also a consideration in this study besides the frequency of grounding.
Risk assessment due to ship collision

In general, the risk of collision is calculated using equation (1) where $P$ is the probability of collision while $C$ is the consequence of a collision. In this study, the probability of collision $P$ is obtained according to the value given by Fujii et al. [5] as given in equation (2). $N_a$ is the number of candidate ships involved in a collision or grounding and $P_c$ is a causation factor that is the probability by considering the causes of the events. These equations may also apply to different cases of applications [6,7].

$$R = P \times C$$  \hspace{1cm} (1)

$$P = N_a \times P_c$$  \hspace{1cm} (2)

Probability for collisions is highly contributed by several things including human error, propulsion failures, machinery failures, and external factors such as bad weather. Causation probabilities can be calculated using the scenario and synthetic approaches. The scenario approach is carried out statistically based on collision event data that has occurred at a particular location while the synthetic approach can be done using the Bayesian Network approach. Bayesian networks use Bayesian inference to compute the probability of occurrences. Bayesian networks employ graphical to model conditional dependence, and therefore causation, by representing conditional dependence by edges in a directed graph. Bayesian networks are considered the right method to bridge the gap between analysis and formulation [8].

WRAP Method for calculating ship collision frequency

iWRAP is a method adopted by the IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities) on the iWRAP MK2 software used to calculate the frequency of collisions and grounding based on formulas formulated by Fujii et al. [5] and Macduff T [9]. The collision frequency $\Lambda_{col}$ is calculated by equation (3) where $P_c$ is the causation factor while $N_G$ is the geometric number.

$$\Lambda_{col} = P_c \times N_G$$  \hspace{1cm} (3)

In this study, the causation factor is determined for each type of accident regarding iWRAP default causation probabilities. All candidates ship that has the potential to experience a collision were grouped by type of ship, dimensions, cargo type, and speed.

Head-on collision and overtaking collision

The frequency of head-on and overtaking collisions is influenced by the length of the segment, $L_w$, the frequency of ships passing on the lane in a certain period, and based on the type of ship, denoted by $Q_i$ and $Q_j$. The speeds of the ship are notated by $V_i$ and $V_j$ while the geometric distribution of the ships passing on the lane, is denoted by $f(y)$ and $f_j(y)$. Distribution of ships crossing the shipping lane is assumed to be normally distributed with the channel axis being the average value of the ship's
crossing collisions and can be calculated with the following equation.

\[ N_{G}^{\text{head-on}} = L_{W} \sum_{i,j} P_{G,ij}^{\text{head-on}} \frac{V_{ij}}{V_{ij}} (Q_i Q_j) \]  \hspace{1cm} (4)

where the notation \( V_{ij} = V_i + V_j \) is the relative speed between the two ships that move along the path and \( P_{G} \) is the probability of the two ships colliding when moving in the opposite direction on a path. \( P_{G} \) can be calculated by the following equation

\[ P_{G} = \Phi \left( \frac{B_{ij} - \mu_{ij}}{\sigma_{ij}} \right) - \Phi \left( - \frac{B_{ij} - \mu_{ij}}{\sigma_{ij}} \right) \]  \hspace{1cm} (5)

\( \Phi \left( x \right) \) states that the calculation is done using the normal distribution, \( \mu_{ij} = \mu_i + \mu_j \), expressed as the mean distance between two vessels on each path. \( \sigma_{ij} \) is expressed as \( \sigma_{ij} = \left( (\sigma_i)^2 + (\sigma_j)^2 \right)^{0.5} \) which is the standard deviation of each lane, and \( B_{ij} = (B_i + B_j)/2 \) is expressed as the mean width of the ship passing through the lane. The frequency of head-on collision, which is expressed as \( L_{col}^{\text{head-on}} \) is obtained from the multiplication of the geometric number \( N_{G}^{\text{head-on}} \) with the causation factor of the head-on collision \( P_{c}^{\text{head-on}} \). To calculate the candidate ships that have the potential to experience overtaking collisions, the equation (4) is used. To calculate the relative speed in the overtaking collision scenario, the formula \( V_{ij} = V_i - V_j \) can be used, if the value of \( V_{ij} < 0 \) then ship \( i \) is unable to overtake ship \( j \). Hence, the equation for calculating ship candidates with the potential to experience overtaking collisions is given in equation (6).

\[ P_{G,ij}^{\text{head-on}} = P \left[ y_i - y_j < \frac{B_i + B_j}{2} \right] - P \left[ y_i - y_j < - \frac{B_i + B_j}{2} \right] \]  \hspace{1cm} (6)

2.2.2. Crossing collision

Crossing collision is influenced by the angle formed between two lanes at an intersection. The angle formed is represented by the notation \( \theta \) (Figure 4). The value of the geometric number of potential ship candidates experiencing crossing collisions can be calculated using equation (7).

\[ N_{G}^{\text{crossing}} = \sum_{i,j} \frac{Q_i Q_j}{V_i V_j} D_{ij} V_{ij} \frac{1}{\sin \theta} \text{ for } 10^\circ < [q] < 170^\circ \]  \hspace{1cm} (7)

The notation \( V_{ij} \) represents the relative speed of the two ships that have the potential to experience crossing collisions and can be calculated with the following equation.

\[ V_{ij} = \left( (V_i)^2 (V_j)^2 - 2 \cdot V_i \cdot V_j \cdot \cos \theta \right)^{0.5} \]  \hspace{1cm} (8)

\( D_{ij} \) is defined as the diameter of the collision area as calculated as equation (9) and shown in Figure 5.

\[ D_{ij} = \frac{L_i V_i + L_j V_j}{V_{ij}} \sin \theta + B_j \left\{ 1 - \left( \sin \theta \frac{V_i}{V_{ij}} \right)^2 \right\} + B_i \left\{ 1 - \left( \sin \theta \frac{V_j}{V_{ij}} \right)^2 \right\} \]  \hspace{1cm} (9)

Figure 4. The angle of a crossing collision

Figure 5. The diameter of the collision area
2.3. Ship grounding

As on the probability of collision, grounding frequency, \( A_{\text{ground}} \) is also calculated by considering causation factor \( P_c \) and geometric number \( N_G \).

\[
A_{\text{ground}} = P_c \times N_G
\]  

(10)

The geometric number is calculated for the candidate ship that has the potential to grounding. Two conditions of grounding are analyzed, powered grounding and drifting grounding. All candidates are grouped according to ship type, dimension, speed, and type of cargo. The default value recommended by iWRAP is used in frequency calculation due to grounding.

3. Consequence analysis

In the event of a collision or grounding, the ship has the potential to suffer damage to the hull which can result in oil spills came from fuel or cargo carried by ship. This study simulates the dispersion of oil by considering several factors such as wind speed and direction, volume, and time. The oil direction and volume of dispersion were predicted using GNOME. This software can estimate how much oil spreads on the sea, reaches the shoreline, or dispersed to the air.

4. Result and discussions

The data used in this study is on-year Automatic Identification System data (2017) which is projected up to the year 2037 by considering an increase in the number of traffic by 2.56% per year. The steps taken in frequency analysis using the iWRAP method are; configuring traffic data, traffic density, define legs/waypoints, define the lateral distribution, and calculate the frequency of collision/grounding. Table 1 and Table 2 show the number of traffic for each ship type and length for through traffic (traffic that utilizes IASL II) and crossing traffic (traffic that cuts the IASL II) respectively.

### Table 1. Projected number of traffics that pass through IASL II (through traffic)

| Length (m) | Crude Oil | Product Tanker | Chemical Tanker | Gas Tanker | Cont. | General Cargo | Bulk Carrier | Ro-Ro Cargo | Passenger | Fast Ferry | Support Ship | Fishing Ship | Pleasure Boat | Other Ship |
|------------|-----------|----------------|-----------------|------------|-------|---------------|--------------|-------------|------------|------------|--------------|--------------|---------------|------------|
| 0-25       | 0         | 2              | 0               | 0          | 0     | 0             | 0            | 0           | 14         | 8          | 42           | 0            | 0             | 0.132      | 0.15        |
| 25-50      | 0         | 0              | 0               | 0          | 0     | 0             | 0            | 0           | 0          | 0          | 0            | 0            | 0             | 0.94       | 0           |
| 50-75      | 0         | 0              | 0               | 0          | 0     | 0             | 0            | 0           | 0          | 0          | 0            | 0            | 0             | 0          | 0           |
| 75-100     | 71        | 52             | 5               | 0          | 0     | 36            | 2            | 0           | 167        | 64         | 182          | 0            | 0             | 0.94       | 0           |
| 100-125    | 39        | 73             | 21              | 0          | 9     | 64            | 0            | 0           | 8          | 0          | 3            | 17           | 3             | 0.68       | 0           |
| 125-150    | 0         | 0              | 9               | 0          | 0     | 2             | 0            | 2           | 0          | 0          | 0            | 0            | 0             | 0.2        | 0           |
| 150-175    | 0         | 0              | 0               | 0          | 0     | 3             | 3            | 0           | 6          | 0          | 0            | 0            | 0             | 0          | 0           |
| 175-200    | 9         | 0              | 555             | 0          | 0     | 553           | 0            | 11          | 0          | 3          | 2            | 3             | 0             | 0          | 0           |
| 200-225    | 0         | 0              | 0               | 0          | 0     | 1106          | 1106         | 2           | 0          | 0          | 0            | 0             | 0             | 0          | 0           |
| 225-250    | 0         | 553             | 0               | 0          | 0     | 1106          | 0            | 9           | 0          | 0          | 0            | 0             | 0             | 0          | 0           |
| 250-275    | 553       | 1106           | 0               | 0          | 0     | 379           | 0            | 3           | 0          | 0          | 0            | 0             | 0             | 0          | 0           |
| 275-300    | 0         | 0              | 553             | 0          | 0     | 3873          | 0            | 8           | 0          | 0          | 0            | 0             | 0             | 0          | 0           |
| 300-325    | 0         | 0              | 0               | 0          | 0     | 2766          | 0            | 0           | 0          | 0          | 0            | 0             | 0             | 0          | 0           |
| 325-350    | 0         | 0              | 0               | 0          | 0     | 0             | 0            | 0           | 0          | 0          | 0            | 0             | 0             | 0          | 0           |
| 350-375    | 0         | 0              | 0               | 0          | 0     | 0             | 0            | 0           | 0          | 0          | 0            | 0             | 0             | 0          | 0           |
| 375-400    | 0         | 0              | 0               | 0          | 0     | 0             | 0            | 0           | 0          | 0          | 0            | 0             | 0             | 0          | 0           |
| Sum        | 673       | 1785           | 588             | 553       | 9     | 105           | 9788         | 1106        | 226        | 71          | 227          | 20            | 232           | 112        |

### Table 2. Projected number of traffics that cuts IASL II (crossing traffic)

| Length (m) | Passenger | Fast Ferry | Support Ship | Fishing Ship | Pleasure Boat | Other Ship |
|------------|-----------|------------|--------------|--------------|---------------|------------|
| 0-25       | 2         | 8505       | 0            | 3331         | 2645          | 2          |
| 25-50      | 0         | 0          | 0            | 3178         | 693           | 0          |
| 50-75      | 0         | 0          | 0            | 0            | 0             | 0          |
| 75-100     | 10947     | 1047       | 64           | 0            | 0             | 3          |
| 100-125    | 0         | 0          | 0            | 0            | 0             | 0          |
| 125-150    | 0         | 0          | 0            | 0            | 2             | 0          |
| 150-175    | 0         | 0          | 0            | 0            | 0             | 0          |
| 175-200    | 0         | 0          | 0            | 2            | 0             | 0          |
| Sum        | 10948     | 9552       | 64           | 6511         | 3339          | 5          |
In addition to traffic data based on the length and type of ship, some inputs are also given in calculations such as average draft, breadth, and speed of the ship. Figure 6 shows the legs design referring to historical data of ship routes operating in the Lombok Strait. Figure 7 shows the analysis of each leg where the bell shape on each leg shows the distribution of ships in each leg. Table 3 shows the summary of frequency analysis for each type of collision considered in this study. Total annual collision including grounding is $4.73 \times 10^{-1}$ and in terms of frequency analysis, the risk due to collision is acceptable since the annual frequency of collision is less than unity.

![Figure 6. Design legs](image1)

![Figure 7. iWRAP analysis](image2)

**Table 3. Summary of frequency analysis**

| Type of Hazard       | Traffic Leg | Sum         |
|----------------------|-------------|-------------|
|                      | Through Traffic | Crossing Traffic |     |
| Head-on Collision    | 2.76 x 10^{-1} | 9.19 x 10^{-1} | 2.85 x 10^{-1} |
| Overtaking Collision | 4.57 x 10^{-2} | 3.12 x 10^{-3} | 4.88 x 10^{-2} |
| Crossing Collision   | 1.10 x 10^{-1} |             |             |
| Merging Collision    | 2.73 x 10^{-2} |             |             |
| Bend Collision       | 1.54 x 10^{-3} |             |             |
| Grounding            | 6.89 x 10^{-7} |             |             |
| **Total Annual Collision** |             |             | $4.73 \times 10^{-1}$ |

The oil spill dispersion scenario is carried out by assuming that a collision involving a tanker occurs in the crossing area between ships passing on IASL II and ships crossing IASL II from the Padang Bai side in Bali to the Lembar in Lombok. It is assumed that the point of occurrence of crossing collision is 8° 38’ 91'' S and 115° 44’ 02” E. The speed and direction of the wind and ocean currents at the location of the oil spill using data recommended by the GNOME Online Oceanographic Data Server (GOODS). There are two conditions in the direction of the wind and sea current that are
used, towards northwest and southwest. The tanker used in the simulation has a length of 261 m with a capacity of 150,000 dwt. The same data used by Van De Wiel et al. [10] is utilized. Based on their study, one tank with a volume of 14,561 m$^3$ is estimated to spill in the amount of 11,970 m$^3$.

Figure 8 shows the distribution of oil where the wind direction is northwestward for each time of 4 hours (a), 8 hours (b), and 12 hours (c). In this scenario, after 12 hours of simulation, spilled oil does not reach to the MPA of Nusa Penida. After 12 hours, there were about 86.4% oil spills floating on the surface of the seawater, and 13.6% dispersed into the air. Within 12 hours, of the 86.4% oil spills that float, no spills reach the shoreline.

![Figure 8. Oil dispersion when wind and sea current heading to the northwest](image)

Figure 9 shows the results of the simulation of the distribution of oil spills when wind and sea current heading to the southwest from the point of impact. It appears that, after 8 hours, the oil spill reach to MPA of Nusa Penida. Where after 12 hours of simulation, there were about 70.6% of spills floating above the water surface, 15.9% of spills would reach the MPA and 13.6% were dispersed into the air. Based on the results of the simulation, the response from the authorities in dealing with the spread needs to be done on the condition if a collision occurs in the crossing area while the wind and sea current are heading southwest.

![Figure 9. Oil dispersion when wind and sea current heading to the southwest](image)

5. Conclusion
Based on collision analysis referring to projected traffic data in the Lombok strait, the total annual frequency of collision is $4.73 \times 10^{-1}$. When referring to frequency analysis, risks due to collisions are still at an acceptable level since the annual frequency is lower than unity. The annual frequency has considered several types of collisions including head-on, overtaking, crossing, merging, bend collision as well as grounding. In addition to the study, analysis of the consequences of ship collisions was also
carried out. The analysis of the distribution of oil spills involving tanker ship collision at the crossing location between IASL II and crossing traffic was carried out by considering two conditions of wind and sea currents; heading northwest and southwest. The simulation results show that the conditions when the direction of the wind and sea currents heading to the southwest will result in a higher impact because oil spilled can reach to the MPA of Nusa Penida. For this reason, the fast response of the authorities in mitigating the spread needs to be done especially in the condition when the collision occurs in the crossing area and the wind leads to the southwest.

**Future Direction of Study**
Maritime Safety Committee (MSC), 101 session, 5-14 June 2019 has approved and adopted new traffic separation schemes (TSS) and associated routeing measures and of precautionary areas with recommended directions of traffic flow in the Lombok Strait [11]. The TSS aims to minimize the risk of collision between ships and grounding. Further studies related to how efficient the TSS can reduce the impact of ship collisions in this area will be conducted.

**References**
[1] IMO Maritime Safety Committee Resolution MSC.72(69), Adoption designation, and substitution of archipelagic sea lanes, adopted on 19 May 1998.
[2] https://www.marinetraffic.com
[3] Kristiansen S 2005 Maritime Transportation: Safety Management and Risk Analysis (Butterworth-Heinemann; 1 edition)
[4] Dong Y and Frangopol M 2015 Probabilistic ship collision risk and sustainability assessment considering risk attitudes J. of Structural Safety. Volume 53, pp. 75-84
[5] Fujii, Yamanouchi, and Mizuki 1974 The probability of stranding. Some factors affecting the frequency of accidents in marine traffic J. of Navigation, Vol. 27, No.2, pp. 239-243
[6] AAB Dinariyana, Ayudia P G, Ketut Buda Artana, AA Masroeri, I Made Ariana, Yeyes Mulyadi 2016 Study on selecting platform decommissioning methods and analyzing the frequency of ship collisions during the decommissioning process (in bahasa) Jurnal Teknik BKI, 3th Edition
[7] AAB Dinariyana, Ketut Buda Artana and Pandhu H. Amarta 2018 Ship collision risk assessment at water area of container terminal due to marine traffic in the Surabaya West Access Channel, MASTIC 2018 pp. 174-181 DOI: 10.23977/mastic.018
[8] Jensen F V 1996 Introduction to Bayesian Networks (Springer-VerlagBerlin, Heidelberg)
[9] MacDuff, T 1974 The probability of vessel collisions Ocean Industry
[10] Van De Wiel, G. & J. René van Dorp 2011 An oil outflow model for tanker collisions and groundings Annals of Operations Research volume 187, pp. 279–304
[11] IMO 2019 COLREG.2/Circ.74 New traffic separation schemes