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# Grounding Probability in Narrow Waterways

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The Strait of Istanbul is one of the world's busiest, narrowest and most winding waterways. As such, there is a high grounding probability for vessels. Although a number of grounding probability models exist, they have been deemed unsuitable by local maritime experts, due to their insufficient stopping distance criteria for narrow waterways. Thus, there is a need for a new model. This paper proposes a two-component grounding probability model that multiplies the geometric grounding probability (calculated with a kinematic-based model) with the causation probability (calculated with a specially designed Bayesian network). The geometric probability model is improved in terms of stopping distance parameters and the Bayesian network is crafted for narrow waterways. The model is then deployed with pre-determined parameters within the Strait of Istanbul to run risk analysis scenarios. The results, validated with actual grounding records, show that the causation probability is the key component for quantifying the probability of grounding in narrow waterways. If navigated without frequent evasive manoeuvres, grounding would be almost inevitable. Although this study focuses on the Strait of Istanbul, the proposed approach can be applied to research into grounding probability of vessels navigating through other waterways.

KEYWORDS

1. Human Factor. 2. Modelling. 3. Risk. 4. Straits.

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## 1. INTRODUCTION.

1.1. *Context.* This paper focuses on estimating the grounding probability of vessels while navigating in narrow waterways in order to enhance risk analysis in such channels. The Strait of Istanbul (the Strait), one of the narrowest waterways in the world, is used as a case study. The Strait is a natural strait that separates the European and Asian continents and links the Sea of Marmara and the Black Sea. The channel is 31 km in length, averages 1·5 km in width (being just 660 m at the narrowest point), and has a depth of between 30 and 120 m. While transit vessel traffic used to be two-way in the Strait (Turkish Straits Maritime Traffic Regulations (TSMTR), 1998), due to Marmaray railway tunnel construction in 2005, vessel traffic has become primarily unidirectional (Marmaray – Maritime Pilot, 2019). Vessels entering the Strait from the north (navigating to the south) are called southbound vessels and vessels entering the Strait from the south (navigating to the north) are called northbound vessels.

1.2. *Problem.* The Strait is an extremely busy waterway. Around 46,000 ships travel through it each year, making traffic on the Strait three times heavier than the Suez Canal and four times heavier than the Panama canal. This leads to a high propensity for accidents. Ince and Topuz (2004) calculated that there are 40 marine accidents per 100,000 vessel passages in the Strait. Many of these accidents are attributed to physical factors, such as strong currents and low visibility (Akten, 2004). However, of particular importance is the narrow and winding nature of the waterway. This makes distances between waypoints short, often giving a vessel a very limited stopping distance. These physical factors, combined with the high traffic density, make the Strait one of the riskiest waterways in the world. Thus, a grounding probability model is needed to calculate the probability of vessel accidents within the Strait.

1.3. *Existing solutions.*

1.3.1. *The grounding probability model.* To calculate grounding probability, two models have been developed: the geometric model (which calculates the probability of a ship being on an accident course); and the grounding causation probability model (which calculates the probability of a ship not taking evasive manoeuvres). The grounding probability ($P_{RG}$) can then be ascertained by multiplying the geometric probability with the grounding causation probability, as outlined in Fujii et al. (1974):

$$P_{RG} = P_{GeoGrn} * P_{CausGrn} \tag{1}$$

where $P_{GeoGrn}$ is the geometric probability of being on a grounding course while navigating blindly and $P_{CausGrn}$ is the causation probability of being incapable of taking evasive actions to avoid grounding.

1.3.2. *Limitations in existing studies of the geometric grounding probability model.* Macduff (1974) developed a grounding probability model for maritime risk analysis in the Dover Strait. In the study, the geometrical probability of grounding was estimated as:

$$P_{GeoGrn} = \frac{4 * T}{\pi * C} \tag{2}$$

where $T$ is the track length (or stopping distance) of the vessel and C is the width of the waterway. $T$ is primarily a function of the size and speed of the ship, which is estimated to be roughly equal to 20 times the length (L) of the ship. However, Macduff (1974) applied this equation to the Dover Strait, which is considerably wider than a "narrow waterway" (approximately 20 times wider than the Strait). On consultation with the Strait Vessel Traffic Service (VTS), experts and pilot captains opined that the estimation for track length (20*L) used in Macduff's study does not apply in narrow waterway conditions, such as the Strait.

Another study that draws upon the grounding probability model is Mazaheri's (2009) study on shipping in the Gulf of Finland. In this study, like Macduff's, the dynamic position of vessels is considered. However, Mazaheri modifies the equation to Equation (3):

$$P_{GeoGrn} = \frac{4 * T}{\pi * C} = \frac{4 * V * \alpha}{\pi * C} \tag{3}$$

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where V is the speed of the vessel under consideration and $\alpha$ is the average duration between two consecutive position checks of the vessel. However, similar to Macduff's study, even though modified, Mazaheri's formula was originally developed for longer water domains, such as the Gulf of Finland where the narrowness of the waterway does not pose an imminant threat as it does in the Strait. Therefore, a new geometric grounding probability model is developed in this study.

1.3.3. *Bayesian networks for calculating grounding causation probability.* The causation probability of grounding accidents contains many uncertainties. Bayesian networks allow for the modelling of real-world applications in which uncertainty is confronted. Probability theory then quantifies this uncertainty via probabilistic models. In this general context, Bayesian networks use Directed Acyclic Graphs (DAG) that are used in reasoning for uncertainty. Bayesian networks consist of a set of variables (nodes) and a set of directed arcs among the nodes. These graphical models indicate the conditional independencies between nodes, whose states are mutually exclusive.

In a Bayesian network:

$$P(X_1, \ldots, X_n) = P(X_1 = x_1, \ldots, X_n = x_n) \tag{4}$$

shows the joint probability distribution of $n$ variables, $X_i$ being in state $x_i$ for $i = 1, \ldots n$.

The joint probability distribution might also be written as:

$$P(X_1, \ldots, X_n) = \prod_{i=1}^{n} P(x_i | x_{parents:(i)}) \tag{5}$$

where $x_{parents:(i)}$ are the parents of $i$.

Since Bayesian networks are DAG:

$$P(X_1, \ldots, X_n) = \prod_{i=1}^{n} P(x_i | x_{i=1}, \ldots, x_1) \tag{6}$$

The marginal distribution of a node in a Bayesian network is computed as:

$$P(X_i) = \sum_{x_1} \cdots \sum_{x_{i-1}} \sum_{x_{i+1}} \cdots \sum_{x_N} P(X_1, \ldots, X_n) \tag{7}$$

The conditional distribution of a variable in a Bayesian network is computed as:

$$P(X_i | X_j) = \frac{P(X_i | X_j)}{X_j} \tag{8}$$

The steps in building a Bayesian network are:

- The nodes and the arcs among these nodes are defined.
- A sensible DAG model is designed.
- Conditional probabilities for the states of the nodes in the network are computed.
- Inference algorithms are applied to estimate the conditional probabilities given some observed nodes (Wiegerinck et al., 2013).

1.3.4. *Existing studies using Bayesian networks for calculating grounding causation probability.* There are a number of existing studies that draw on Bayesian networks to calculate grounding causation probability. For example, Or and Kahraman (2002) estimated marine accidents on the Strait using a Bayesian inference. In addition, Hänninen and Kujala (2012) looked at causation probability and built a Bayesian network to estimate collision causation probability. Furthermore, Hänninen (2014), discussed the advantages and challenges of Bayesian Networks applied in maritime models. Thus, utilising a Bayesian model for calculating grounding causation probability is a tried and tested approach. As such, this work draws on this approach in its grounding probability model. However, a network that focuses on estimating the grounding causation proability is specially devised for vessels navigating in narrow waterways.

1.4. *Aim of this research.* This study expands on the work of Macduff (1974) and Mazheri (2009) by adapting their geometric probability formulae to create a new kinematic-based formula to calculate the geometric grounding probability to suit the narrow and winding conditions in the Strait where stopping distances are shortened. Furthermore, this study expands on the work of Hänninen and Kujala (2012), Hänninen (2014) and Or and Kahraman (2002) by utilising a Bayesian network to allow for uncertainty when estimating the grounding causation probability. Thus, through adapting existing models for geometric grounding probability, and by adapting existing Bayesian networks for grounding causation probability, this research aims to create a new model that can estimate the grounding probability of vessels navigating in narrow waterways. The ultimate aim of the study is to enhance risk analysis models in such channels.

## 2. METHODOLOGY.

2.1. *The vessel accident model.* In order to create a grounding probability model for the Strait, a vessel accident event model was drawn upon (Kristiansen, 2005). As described previously, vessel accident events (Acc) occur at the intersection of two events: a ship being on an accident course (Geo); and a ship not taking avoiding manoeuvres (Caus).

Accordingly, P(Acc) is calculated by:

$$P(Acc) = P(Geo \cap Caus) = P(Geo, Caus) \tag{9}$$

and:

$$P(Acc) = P(Geo) * P(Caus|Geo) \tag{10}$$

In this study, based on discussions with various experts such as pilots in the Strait and VTS, it is assumed that a vessel's ability/inability to make avoiding manoeuvres to avoid an accident is marginally independent of that vessel being on the accident course. Therefore:

$$P(Acc) = P(Geo) * P(Caus) \tag{11}$$

2.2. *Estimating the geometric grounding probability in narrow waterways.* This study proposes the following equation to estimate the geometric grounding probability,

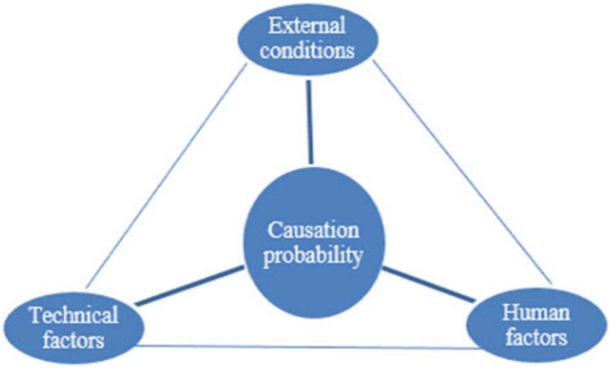


Figure 1. Factors affecting causation probability.

$P_{Geo}(i,j)$, for a vessel $i$ navigating along some sector $j$ of a narrow waterway:

$$P_{Geo}(i,j) = \begin{cases} \frac{T_i}{L_j} = \frac{V_{ij} * \alpha}{L_j} & if \quad \frac{T_i}{L_j} < 1 \\ 1 & if \quad \frac{T_i}{L_j} \geq 1 \end{cases} \tag{12}$$

where $T_i$ is the track length of ship class $i$, which is defined as the length at which the corrective actions/manoeuvres initiated by the captain (usually at position checks) are affected, $L_j$ is the length of sector $j$ of the waterway, $V_{ij}$ is the speed of vessel $i$ at sector $j$ of the waterway and $\alpha$ is the average duration between two consecutive position checks of the vessel. The total number of position checks is assumed to be roughly equal to the number of major course changes in the Strait, which is 12 (leading to the Strait being divided into 13 sectors, as proposed by Altan and Otay (2017)). Accordingly, since the approximate transit time in the Strait is around 90 minutes, $\alpha$ is estimated as $90/12 = 7.5$ minutes. The proposed geometric grounding probability formula implies that vessel $i$ navigating through sector $j$ would ground at the corner point of sector $j$ if the length of the sector $j$ is less than or equal to the stopping distance of vessel $i$ and if no alteration of course is made towards the next leg of the passage. Thus, the geometric grounding probability in the Strait is essentially the probability that the vessel will not execute a course alteration at the end of its current sector, and will proceed to ground unless it stops before doing so.

2.3. *Bayesian network for calculating grounding causation probability.* As described previously, the grounding causation probability $P_{CausGrn}$ is the probability that in a vessel which is on a grounding course, the captain takes no action or is unable to avoid a grounding accident. In order to identify conditions and factors to include in the developed Bayesian network to identify $P_{CausGrn}$, we drew upon aspects outlined in the ANNEX II: Risk Assessment-Large Passenger Ships-Navigation Report (2019). From this, two groups of factors and one group of external conditions emerged (Figure 1).

Aspects included in this study's Bayesian network are grouped into: external conditions; technical and human factors.

Regarding external conditions, these factors externally affect the captain's manoeuvring ability (that is, the captain has no control over them). Some examples of external conditions are explained below:

- Wind: This node contains the active wind conditions in the Strait. The conditional probabilities for the states of this node are estimated through wind data from the Turkish State Meteorological Services (TSMS, 2018) for the past ten years. The wind speed is then categorised in the Beaufort wind scale.
- Sector: This node represents the 13 sectors which are defined by Altan and Otay (2017). The division is based on the navigational and geographical differences.
- Transit Vessel Density: This node groups the density of transit traffic in the Strait. The conditional probabilities for the states of this node are based on Altan and Otay (2018).
- Visibility: This node reflects the visibility conditions in the Strait. The conditional probabilities for the states of this node are compiled through the TSMS (2018).
- Ship Types in Lane: Marine traffic in the Strait has been primarily uni-directional since 2005. However, small vessels (classes D and F in Table 1) and passenger vessels (class P in Table 1) are allowed to enter the Strait against the primary traffic flow direction at any time. The conditional probabilities for the states of this node are estimated based on the VTS traffic data.

Table 1. Vessel classification in the Strait (Candanoglu, 2013).

| | Tankers and Hazardous Material Carrying Vessels | | Other Cargo Vessels | | Passenger Vessels |
|---|---|---|---|---|---|
| Length (m) | Turkish Flagged Vessels | Other Flagged Vessels | Turkish Flagged Vessels | Other Flagged Vessels | All Flags |
| 75> | F | | F | | |
| 75-100 | D | | | | |
| 100-150 | C | | | | |
| 150-200 | B | | C | | P |
| 200-250 | A | | | | |
| 250-300 | | | E | | |
| >300 | T6 | | | | |

The captains are assumed to have control over their vessels' status affected by the pilotage factors. These factors are explained below:

- Bridge Resource Management (BRM): According to the International Maritime Organization (IMO), BRM is an effective management tool enabling the bridge team to use all available vessel resources for a safe voyage (The Navigator, 2014). The probabilities for the states of this node are gathered through expert opinion.
- Safety Culture: This node reflects the safety comprehension of the vessel crew. The probabilities for the states of this node are obtained through expert opinions.
- Machine Failure: This node accounts for the engine failures of vessels in the Strait. The conditional probabilities for the states of this node are derived from past accidents reported by the VTS.

- Steering Failure: This node accounts for steering failures of vessels in the Strait. The conditional probabilities for the states of this node are derived from past accidents reported by the VTS.
- Pilot Availability: According to the rules and regulations, large tankers and hazardous cargo carrying vessels (class A and class B vessels in Table 1) are highly recommended to take pilots during their transit in the Strait (Turkish Straits Sea Traffic Scheme, 2018). This service is also recommended to other vessels. The conditional probabilities for the states of this node are obtained from VTS statistics.

Human factors account for the the captain's vessel manoeuvring ability, as the captain is assumed to have full control over the ship. Some of them are explained below. The conditional probabilities for these states of these nodes are all obtained via expert opinion.

- Familiarity: Having navigation experience in the Strait enhances navigation safety.
- Vigilance (of Officer Of the Watch - OOW): While keeping watch on the bridge, the OOW is the representative of the ship's captain and has total responsibility for the safe and smooth navigation of the ship. The OOW is also in charge of the bridge team, who are there to support the OOW in the navigation process. This node measures the effectiveness of the OOW.
- Attention: This node indicates the caution capability of the captain.
- Causation Factor: This is the target node in the estimation of the grounding causation probability. It is the probability of being unable to avoid grounding for a vessel on a grounding course.

The conditional probabilities for the states of the Bayesian network are gathered in several ways. The conditional probabilities for the node "Local vessel density" are obtained from local shipping providers, for the node "Pilot availability" they are obtained from VTS statistics, the nodes "Attention", "Visual detection", "Fatigue", "Assessment", "Navigation system detection", "Detection", "Action" and "Loss of control" are obtained from expert opinion. Since the data is insufficient to obtain the conditional probabilities for the states of the "Current" node, conditional probabilities of wind types are associated with current states. For example, the probability of a strong current given that a strong southwestern (northeastern) wind is prevailing is assumed to be 1 whereas the probability of mild current given that a mild southwestern (northeastern) wind is prevailing is assumed to be 1. Vessels transiting the Strait are classified based on their cargo type, length and flag (Table 1). T6 vessels are the rarest class transiting through the Strait (at most five times in a year), therefore they are embedded in class A vessels (they have the similar entrance rules) in this study. Class A vessels are the most important regarding perceived risk and accordingly they make up the backbone of the Strait vessel scheduling system. They carry hazardous materials, hence in order to diminish the risk, they may enter the Strait only during day time and with wide time/distance separation between two consecutive such vessels. Class B vessels also carry hazardous materials and if there exists no class A vessel during day time, class B vessels may enter the Strait, otherwise they may pass the Strait at night time. Class C vessels carry both hazardous and nonhazardous cargo varying by their lengths. Class D vessels are the most numerous (59% of all entrances) and have the least passage priority with class F vessels which are small Turkish flagged vessels. Class E vessels are the largest vessels carrying nonhazardous material and class P vessels are passenger ships.

Based on all the aspects described above, the following Bayesian network is designed (Figure 2). It is then solved through the Genie software package in order to estimate the grounding causation probabilities of vessel classes in different sectors.

2.4. *Developed model for grounding probability for narrow waterways.* To finalise the grounding model, geometric probabilities calculated with Equation (12) are multiplied with the causation probabilities estimated with a specially designed Bayesian network model as shown below.

$P_{RG}(i,j)$ is the probability of vessel $i$ grounding at sector $j$, as described in Equation (13):

$$P_{RG}(i,j) = P_{GeoGrn}(S(i),j) * P_{CausGrn}(S(i),j) \tag{13}$$

where $P_{GeoGrn}(S(i),j)$ is the geometric grounding probability for vessel $i$ (member of class $S$) at sector $j$ and $P_{CausGrn}(S(i),j)$ is the grounding causation probability for vessel $i$ (member of class S) at sector $j$.

$X_{grounding}$ is the random variable representing the number of vessels which ground for n navigating vessels and $x_{(i,j)}$ is the states indicating whether there is a grounding ($x_{(i,j)} = 1$) or no grounding ($x_{(i,j)} = 0$) for vessel $i$ at sector $j$. Then, the expected number of groundings is computed by the formulae:

$$N_{grounding} = E[X_{grounding}] \tag{14}$$

$$N_{grounding} = \sum_{i=1}^{n} \sum_{j=1}^{13} x_{(i,j)} * P_{RG}(i,j) \tag{15}$$

where $N_{grounding}$ is the expected number of groundings at the considered time period and $n$ is the number of all vessels entering the waterway in one year.

Accordingly:

$$N_{grounding/100,000} = \frac{N_{grounding}}{n} * 100,000 \tag{16}$$

where $N_{grounding/100,000}$ is the expected number of groundings per 100,000 transiting vessels.

## 3. RESULTS AND ANALYSIS.

3.1. *Geometric grounding probability results.* The results in Tables 2 and 3 show that, regarding the northbound and southbound vessels in the Strait, the geometric grounding probability is generally high, implying that a vessel navigating straight ahead in the Strait most probably grounds at or close to the endpoints of the sections. Since Sector 3 is the longest sector, the geometric grounding probabilities for all vessel types in this sector are less than their counterparts in other sectors. Additionally, class D and class F are smaller and slower vessels, with low tracking routes; therefore, the geometric grounding probabilities for these vessel types are lower.

The results shown in Tables 2 and 3 show that the geometric grounding probability for a class A vessel in either direction is the lowest in sector 3 (the longest sector), and sector 13 of southbound traffic (the lowest speed). The geometric grounding probabilities for class B vessels in either direction are high. The geometric grounding probability for class C vessels in either direction is more than 0·71, except in sector 3. Since the geometric probabilities for all vessel classes are very close to one, the causation probability becomes the critical factor.


Figure 2. The Bayesian network model of “Grounding Causation Probabilities”.

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Table 2. Geometric grounding probability of northbound vessels.

| | Vessel Class | | | | | | |
|---|---|---|---|---|---|---|---|
| Sector | A | B | C | D | E | F | P |
| 1 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 |
| 2 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 |
| 3 | 0·53 | 0·55 | 0·52 | 0·42 | 0·53 | 0·40 | 0·53 |
| 4 | 0·86 | 0·89 | 0·85 | 0·68 | 0·86 | 0·66 | 0·86 |
| 5 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 |
| 6 | 1·00 | 1·00 | 1·00 | 0·86 | 1·00 | 0·83 | 1·00 |
| 7 | 0·88 | 0·91 | 0·87 | 0·70 | 0·89 | 0·67 | 0·88 |
| 8 | 0·76 | 0·79 | 0·75 | 0·61 | 0·77 | 0·58 | 0·76 |
| 9 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 |
| 10 | 0·81 | 0·84 | 0·80 | 0·65 | 0·82 | 0·62 | 0·81 |
| 11 | 0·98 | 1·00 | 0·97 | 0·78 | 0·99 | 0·75 | 0·98 |
| 12 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 |
| 13 | 0·88 | 0·91 | 0·87 | 0·70 | 0·89 | 0·67 | 0·88 |

Table 3. Geometric grounding probability of southbound vessels.

| | Vessel Class | | | | | | |
|---|---|---|---|---|---|---|---|
| Sector | A | B | C | D | E | F | P |
| 1 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 |
| 2 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 |
| 3 | 0·67 | 0·71 | 0·68 | 0·62 | 0·53 | 0·60 | 0·53 |
| 4 | 0·97 | 1·00 | 0·99 | 0·89 | 0·86 | 0·87 | 0·87 |
| 5 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 |
| 6 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 |
| 7 | 0·89 | 0·93 | 0·90 | 0·81 | 0·89 | 0·79 | 0·89 |
| 8 | 0·77 | 0·81 | 0·78 | 0·70 | 0·77 | 0·68 | 0·77 |
| 9 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 |
| 10 | 0·86 | 0·91 | 0·88 | 0·79 | 0·82 | 0·77 | 0·82 |
| 11 | 0·92 | 0·97 | 0·94 | 0·84 | 0·99 | 0·82 | 1·00 |
| 12 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 | 1·00 |
| 13 | 0·74 | 0·78 | 0·75 | 0·68 | 0·89 | 0·66 | 0·89 |

Table 4. Grounding causation probabilities in each direction.

| Pre-set state of "the Direction" node | $P_{CausGrn}(*10^{-6})$ |
|---|---|
| Northbound | 4·8915 |
| Southbound | 5·2192 |

3.2. *Grounding causation probability results.* The Grounding Causation Probabilities are calculated with a Bayesian network accounting for the direction of vessels entering the Strait. The results reveal that northbound vessels have a lower causation probability for grounding since they are able to take better evasive action compared to southbound vessels (Table 4).

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Table 5. Effects of factors (Bayesian network nodes) on the causation probability (CP).

| Node | Pre-set States | CP for northbound vessels $*$ ($10^{-6}$) | CP for southbound vessels $*$ ($10^{-6}$) |
|---|---|---|---|
| Season | Winter | 5·5691 | 5·8939 |
| | Spring | 4·6630 | 4·9879 |
| | Summer | 4·4298 | 4·7545 |
| | Autumn | 4·9041 | 5·2289 |
| Day-light | Morning | 4·8808 | 5·2049 |
| | Afternoon | 4·8874 | 5·2119 |
| | Night | 4·9005 | 5·2259 |
| Pilot | Available | 4·3840 | 4·6758 |
| | Not available | 50·4140 | 50·7670 |
| Transit traffic density | Low | 4·8903 | 5·2149 |
| | Moderate | 4·8915 | 5·2163 |
| | High | 4·8928 | 5·2177 |
| Current | Mild | 2·8853 | 3·2101 |
| | Moderate | 7·0286 | 7·3533 |
| | Strong | 9·7437 | 10·0685 |
| Machine failure | Occurs | 400·0000 | 420·0000 |
| | Does not occur | 0·6427 | 0·7155 |
| Fatigue | Regular | 4·6859 | 4·9973 |
| | Over time | 6·0039 | 6·4009 |
| Attention | Attentive | 4·8766 | 5·2004 |
| | Inattentive | 4·9580 | 5·2871 |

The individual effects of various nodes on grounding Causation Probability (CP) are given in Table 5. The results show that, in winter, captains are insufficiently vigilant in taking control of the vessels on potential grounding courses, whereas in summer, adverse meteorological conditions are rare, thus, avoiding actions are easier to manage. Additionally, as the results in Table 5 indicate, since visual detection is more difficult at night, identifying the danger is more difficult; however, daylight enables easier detection of the approaching grounding risk. Table 5 also shows that taking a pilot during the Strait transit dramatically decreases the accident probability. As expected, the grounding causation probability increases as the intensity of the transit traffic density increases. Similarly, the grounding causation probability increases as current speed increases. As the results in Table 5 indicate, machine failure notably increases the loss of control in both directions. Moreover, working overtime increases the grounding causation probability. In addition, careful attention to navigation decreases the causation probability in both directions. In all of the factors analysed, the grounding probability is slightly higher for southbound vessels.

3.3. *Comparison of expected number of groundings with the observed groundings.* Between 2008 and 2014, Turkish Ministry of Transport, Maritime and Communications (2018) reported 17 groundings in seven years whereas the model predicts 21·5 groundings.

Table 6 compares the annual number of groundings per year and number of groundings per 100,000 vessels. The number of groundings per 100,000 vessels is assumed to have a binomial distribution:

$$P(x,n) = \binom{n}{x} * p^x * (1-p)^{(n-x)} \tag{17}$$

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Table 6. Comparison of grounding frequencies.

| | Number of Groundings | Number of Years | Number Vessel Entrances | Groundings per year | Groundings per 100,000 vessels |
|---|---|---|---|---|---|
| Observed | 17·0 | 7 | 347,057 | 2·4 | 4·9 |
| Modelled | 21·5 | 7 | 347,057 | 3·1 | 6·2 |

Table 7. Number of observed groundings in the study period.

| Year | Number of Vessel Entrances | Number of Groundings |
|---|---|---|
| 2008 | 54,396 | 7 |
| 2009 | 51,422 | 4 |
| 2010 | 50,871 | 2 |
| 2011 | 49,798 | 1 |
| 2012 | 48,509 | 1 |
| 2013 | 46,532 | 2 |
| 2014 | 45,529 | 0 |

where $x$ is the random variable denoting the number of groundings, $n$ is the number of vessels transited (100,000) and $p$ is the probability of the vessel grounding.

Since $n$ is large, a Binomial distribution approaches the Poisson distribution:

$$P(x, \lambda)) = \frac{e^{-\lambda} * \lambda^{x}}{x!} \tag{18}$$

where x is the random variable denoting the number of groundings per 100,000 vessels and λ is the average number of groundings per 100,000 vessels.

The probability of having at most k number of groundings is:

$$F(x, \lambda) = \sum_{x=0}^{x=k} \frac{e^{-\lambda} * \lambda^{x}}{x!} \tag{19}$$

Since λ = np, when k = 8:

$$F(8, \lambda) - F(0, \lambda) = 0{\cdot}94$$

Therefore, it is deduced that 94% of the time, the model predicts 1 to 8 groundings per 100,000 vessels, similar to the observed number in this interval which is 4·9 groundings per 100,000 vessels.

In order to better identify the effect of traffic density on the number of groundings, the mathematical model results corresponding to the years of high and low transit traffic realisations are compared with the observed number of groundings in these years (Table 7).

3.3.1. *Grounding comparisons based on high and low transit traffic scenarios.* In order to analyse the effect of transit traffic on the number of groundings, the estimated number of groundings under high transit traffic (based on 2008 data) and under low transit (based on 2013 and 2014 data) traffic are compared with the observed number of groundings in the same years. As displayed in Table 8, on average, 3·2 groundings occur under high traffic and 2·9 groundings occur under low traffic in a year. The results are in line with the expectation that higher (lower) transit traffic increases (decreases) the number of

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Table 8. Comparison of groundings in high and low transit traffic frequencies.

| | Traffic Frequency | Total Vessel Entrances | Number of Groundings | Number of Years | Groundins per year | Grounding per 100,000 vessels |
|---|---|---|---|---|---|---|
| Observed | High | 156689 | 13·0 | 3 | 4·3 | 8·3 |
| | Low | 190368 | 4·0 | 4 | 1·0 | 2·1 |
| Modelled | High | 156689 | 9·7 | 3 | 3·2 | 6·2 |
| | Low | 190368 | 11·8 | 4 | 2·9 | 6·2 |

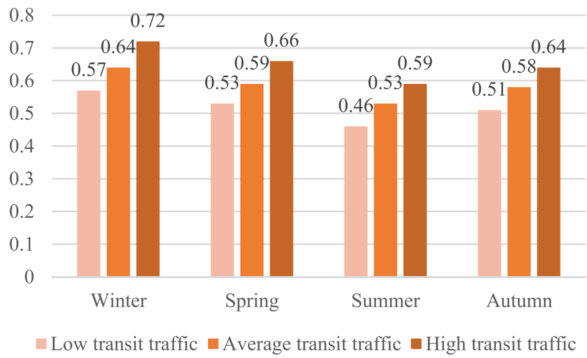


Figure 3. Number of groundings with respect to seasons.

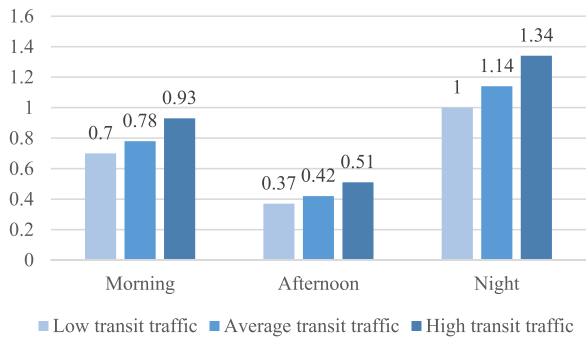


Figure 4. Number of groundings with respect to various times of day.

groundings in both observed and the model results. However, since the number of observed years is short and grounding is a rare event, these results are inconclusive.

3.4. *Scenario analysis for model generated groundings.* In order to observe the effects of season, daylight and vessel type on the expected number of groundings, under various transit traffic density levels, results obtained by Özlem (2018) are used. In this study, a simulation model mimicking the Strait transit traffic was developed in order to generate traffic patterns to provide decision support under various transit vessel traffic flows. Figure 3 displays the effects of season on the expected number of groundings, under predicted average, low and high transit vessel traffic conditions. The figure reveals that the expected number of groundings increases with higher transit traffic. Moreover, grounding

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frequency is highest in winter (due to strong winds and low visibility) and lowest in summer (due to gentler winds and good visibility).

Figure 4 shows the effects of daylight on the expected number of groundings under various predicted transit vessel traffic conditions. The figure shows that the expected number of groundings increases with higher transit traffic levels. Moreover, grounding frequency is highest at night time and lowest in the mornings.

In addition, in the observed data, 52·9% of the groundings involve southbound vessels and in the model results, 52·4% of the groundings involved southbound vessels.

## 4. CONCLUSION.

In this study, a “two component” model was developed to estimate the vessel grounding probabilities in narrow waterways. The “geometric grounding probability” component of the model is based on Equation (12). A Bayesian network was built to estimate “the grounding causation probability” component. The overall grounding probability was assumed to be the product of these two probabilities. The developed model was then deployed to estimate grounding probabilities of vessels under pre-determined scenarios for sensitivity analysis of different factors.

The model was tested using the Strait of Istanbul as a case study. The geometric probability values were found to be close to one which implies that the controlling model to estimate the grounding probability is the causation probability model. The results show that the grounding causation probability is higher for southbound vessels, primarily because the prevailing southerly currents slightly increase the likelihood of the loss of rudder control in that direction. The effects of travel season, daylight and traffic density on the grounding probability were analysed. The results showed that the grounding causation probability was highest in winter, at night and in high traffic density, as expected.

The number of groundings forms the basis for an elaborate risk assessment. The expected number of groundings per year in the Strait was found to be 2·4 whereas the observed number of groundings per year was 3·1. The number of groundings per 100,000 vessels was found to be 4·9 whereas the observed rate was 6·2. Due to a short observation period (7 years) and grounding being a rare event, these results are not very conclusive.

The calculated probabilities were within 30% of observations. In order to better observe the effects of transit traffic on the number of groundings, the overall period (where data was available) was divided into high and low transit traffic scenarios. As expected, the predicted number of groundings increased as the transit traffic increased.

This study is proposed as a basis for a risk analysis of one-way vessel traffic in narrow waterways such as the Strait of Istanbul. It contributes to maritime studies by providing a grounding probability estimation for the Strait and compares the mathematical model results with the observed number of groundings. There are still some aspects open for improvement in future studies. Shoals in the Strait can be considered and the use of real-time traffic data in the geometric probability analysis will better represent the actual conditions in the waterway. Integrating these characteristics to the model could improve the model’s performance and results. Furthermore, vessel accidents are mainly affected by the complex currents in the Strait. This issue can only be resolved by integrating a real-time current measurement system with a hydrodynamic solver into the risk analysis. Moreover, the conditional probabilities of some nodes, such as the transit traffic density and ship types in lanes, were derived from 2014. These probabilities may be refined with long term data. Added to that, some arcs in the Bayesian network (for instance arcs for the “Current” node) for estimating causation probability were not fully utilised due to data insufficiency. If more hydrodynamic data can be compiled, the Bayesian network may be enhanced. Finally, the expert opinion extraction process may be expanded in further studies.

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