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Spatial mapping of encounter probability in congested waterways using AIS

Yigit C. Altan[a,*], Emre N. Otay[b]

[a] Department of Civil Engineering, Bahcesehir University, Istanbul, Turkey
[b] Department of Civil Engineering, Bogazici University, Istanbul, Turkey

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ABSTRACT

Ships in congested waterways are more prone to collision than open sea conditions. Although in most waterways, the overall accident probability is known, their spatial distribution, even for the most dangerous waterways in the world, is not commonly available as a detailed map. Existing solutions distribute the ships along predetermined routes which distorts the actual spatial distribution.

In this study, a collision model is developed based on molecular collision theory. The model allows the use of long-term AIS data as input to calculate the encounter probability in two-dimensional waterways. The model is tested in the Strait of Istanbul, which is divided into sectors and further subdivided into cells. The encounter probability is calculated using vessel kinematics extracted from one-year AIS data.

Results show that the collision probability increases as the narrow passages in the Strait intensify the ship density. Also, sharp turns in the SOI cause additional expansion in collision diameters which further increases the accident probability.

The results are compatible with the observed collision accident locations. The sector-based approach provides a better understanding of the spatial distribution of accidents in high-resolution digital maps which are useful for captains, traffic controllers and other stakeholders to take necessary precautions.

1. Introduction

Maritime accidents affect people directly or indirectly in terms of health, environment and economy. Accident probability assessment is one of the most important steps for deciding preventive actions. Maritime accident probability studies started in 1950 with pure mathematical calculations. These studies do not consider the real sea conditions. Therefore, the results are far away from the reality. Ship to ship collision is one of the most encountered accident types in congested waterways. First studies on ship collision started in 1950s (Nichols, 1950; Sadler, 1957) where the authors relied solely on deterministic formulas and therefore come short in reflecting the real sea conditions (Wylie, 1962). In 1970s, two pioneering works applied the molecular collision theory to maritime accidents (Fujii and Shiobara, 1971; MacDuff, 1974) and introduced the first collision probability theory based on collision diameter. Pedersen (1995) later quantified Fujii and Shiobara's (1971) collision diameter to calculate the probability of causation factor. Montewka et al. (2010) improved the collision diameter as the minimum distance to collision (MDTC), defined as the distance where the collision is unavoidable by any maneuver.

An alternative to molecular collision theory is the ship domain approach where the approach of two ships within a pre-defined distance is defined as a critical situation (Goodwin, 1975) to predict the number of collisions (Goerlandt and Kujala, 2011; Merrick et al., 2003; Shu et al., 2017; Wang and Chin, 2016). According to Wang et al. (2009) study, there are more than one type of ship domain. If the most effective ship domain is not decided for the given waterway, it can cause epistemic uncertainty. A detailed discussion of the uncertainties for maritime applications can be found in (Goerlandt and Kujala, 2014; Merrick and Van Dorp, 2006). However, in molecular collision theory, calculation steps of the parameters are well defined. Therefore, the molecular collision approach is found to be more appropriate for the scope of this study.

AIS data has been used for estimating the accident probability map of a waterway (Ylitalo, 2010) and harbor entrances (Mou et al., 2010) since 2010. These studies have been followed by ship collision risk off the Coast of Portugal (Silveira et al., 2013), accident risk in the Malacca Strait (Maimun et al., 2014; Zaman et al., 2013), ship sinking frequencies in Madura Strait, Indonesia (Mulyadi et al., 2014), near miss detection in Singapore port anchorages (Debnath and Chin, 2016), Northern Baltic Sea (Zhang et al., 2016) and collision probability in the Strait of Messina (Cucinotta et al., 2017). A detailed discussion of the AIS usage for maritime traffic can be found in (Altan and Otay, 2017).

According to literature review the most widely used approach for

* Corresponding author.
E-mail address: yigitcan.altan@gmail.com (Y.C. Altan).

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assessing the accident probability is to analyze the two factors of an accident. One of them is the opportunity of an obstacle (e.g. ship, shoal, etc.) on the way of the ship and the other one is not being able to make evasive maneuvers during the contact time to an obstacle due to loss of navigational control, human errors, meteorological conditions, mechanical failure and etc. These two factors are called as geometric probability and causation probability, respectively.

The pioneering works of Fujii and MacDuff modified the molecular collision probability to model maritime accidents. Studies followed in the literature have proven the reliability of the molecular collision theory for predicting the maritime collisions. Up to now, some approaches have tried to apply the theory to real waterways, but they remained limited within the ship routes. Collision probability of ships outside the pre-determined routes cannot be accounted in such models.

In this paper, a new model is developed to study maritime collision probabilities based on molecular collision theory. Although there are good studies in this field, there are still missing parts in the literature. The main contributions of the paper are:

- Application of theory on a spatial distribution (in section 3.4 and 4)
- Application of data from long-term AIS data in a congested waterway (section 4)
- Comparison with the past maritime collision records (section 5)

These three contribution for the maritime collision theory and application results are discussed in coming chapters.

2. Problem statement and site specific conditions

2.1. Problem statement

In the literature geometric probability is used for representing the probability of obstacles on a given course. In the scope of this study only ships collisions are studied. Therefore, throughout the manuscript the term encounter probability is used for representing the geometric collision probability. Draper and Bennett (1972) assumes that encounter occur when two ships pass within a specified distance of each other. In this study, encounter is defined to occur when distance between two ship centers are equal to collision diameter.

Encounter probability of a waterway represents the maritime risk level without the captain's actions. The result is the encounter probability of ships for a given time period if no evasive maneuver is made. This encounter probability depends on the density of ships, velocities and meeting angles.

In the literature there are many studies for solving the encounter probability of a waterway. These studies consider that ships all travel along designated routes. Their lateral distribution along the routes are assumed by some probability distributions or found based on AIS data. But it is known that ships can make random movements along their paths especially in congested and narrow waterways.

In order to eliminate the route dependence in encounter probability, a 2-D approach similar to finite volume as in the analysis of fluid flow is developed. The considered waterway is divided into sectors considering the major course changes, and these sectors are subdivided into cells in order to analyze the spatial distribution of the ships and encounter probability.

2.2. Site specific conditions: Strait of Istanbul

The Strait of Istanbul (SOI) is one of the most complex waterways in the world in terms of its navigational properties. SOI is a natural navigational channel between Black Sea and Marmara Sea. The sea level difference between these two seas is the main cause of the strong currents during the navigation of 16.8 nm. Variation of the width around 0.81 nm and the 13 turns are causing the fluctuations of the current magnitude and direction during the SOI passage. 309,000 vessel movements consist of transit and local ships with a ratio of 1–8 (Altan and Otay, 2017). The navigational properties and vessel density of the SOI make it a critical waterway for the maritime accidents.

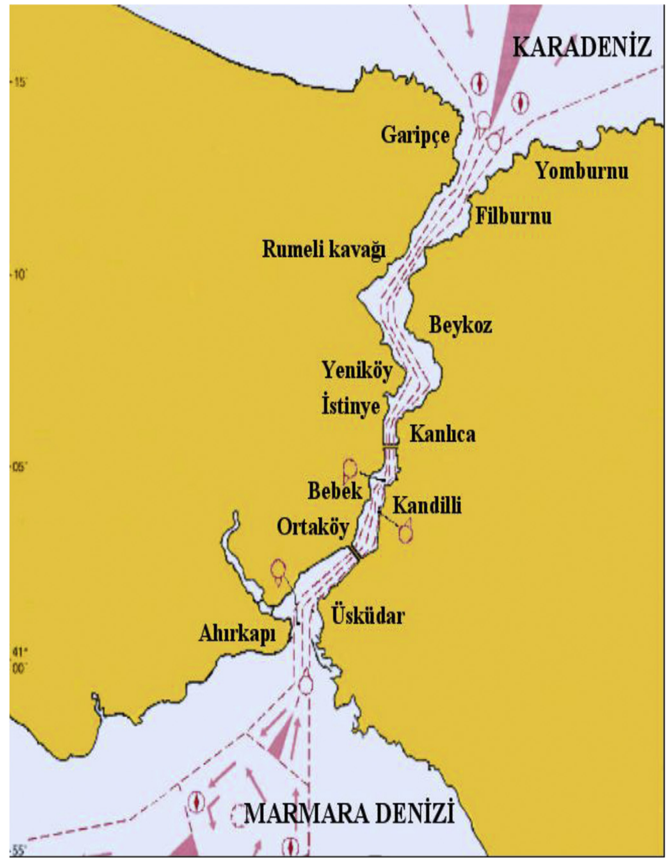

Fig. 1. Traffic separation scheme in the Strait of Istanbul (TSMTR, 1998).

The transit traffic in the SOI is regulated with Traffic Separation Scheme (TSS) as given in Fig. 1 (TSMTR, 1998). The northbound ships are allowed to use the east side of the TSS and southbound ships are allowed to use the west side of the TSS. The local ships (ferries, scheduled and unscheduled passenger ships and etc.) have to keep clear from the transit traffic and they should spend minimum time inside the transit traffic zone. Unless it is necessary, none of the ships are allowed to travel with a speed higher than 10 knots. If there is a ship inside the SOI with a LOA bigger than 200 m, VTS operators may change to unidirectional traffic instead of bidirectional traffic. When unidirectional traffic is used, transit ships are allowed to use the both lanes of the TSS. In addition to these rules, it is recommended to use pilot services but it is not enforced by the rules.

A representative sketch of the local traffic is given in Fig. 2. The redlines represent the designated ferry lines. In addition to these redlines there are private passenger transportation means and their routes and time schedules are not determined exactly. The dashed blackline represents the middle part of the SOI.

Maritime traffic in the SOI including accident locations has been mapped by Kornhauser and Clark (1995) using official paper logs and incident records. Before the availability of real-time electronic data, vessel traffic in the SOI has been analyzed with probabilistic models (Otay and Özkan, 2003; Tan and Otay, 1999; Yazici and Otay, 2009). These models can mathematically estimate long-term vessel distributions and the expected accident frequencies based on statistics of transit vessels. Models helped to understand the statistical characteristics of the transit traffic. However, the detailed navigation patterns, especially of local traffic remained unknown. The first attempt to use AIS data for the traffic analysis in the SOI was based on a two-day visual assessment