Stochastic Modeling of Tanker Traffic through Narrow Waterways

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Abstract

In this paper a stochastic model of tanker traffic is developed to determine the probability of vessel casualties resulting from the transit traffic through a narrow waterway. More specifically, the present study models the collision and grounding probabilities in a waterway resulting from course changes due to hydrodynamic forces acting on the vessel. The computation of vessel positions and the drift probabilities are based on probabilistic considerations of physical quantities that affect navigation including vessel characteristics, randomness of hydrodynamic forces and vessel arrival times. The modeling results provide risk charts that will show the casualty probability across the geometry of the strait at a given time and vessel traffic intensity. Furthermore, the relationship between the traffic intensity and a global measure of casualty risk was analyzed. This preliminary study will be used as a test bed for a more comprehensive model.

1. Introduction

Vessel casualties resulting from oil tanker traffic have important economic and environmental consequences. Especially, if a casualty yields an oil spillage, environmental impacts threaten the ecology while the financial costs may ruin the ship-owner, and even, the liability insurer (Unsworth, 1997; Oshins, 1992). Furthermore, if the casualty takes place in a transit waterway, the entire sea traffic may be blocked for a long period of time affecting other vessels. Since 1960, 1720 oil spills are reported worldwide resulting in a spill volume of around 1.8 billion gallons (Etkin, 1997).

Our study is motivated by the potential threat of the increasing oil tanker traffic through the Turkish Straits. The Strait of Istanbul, also known as the Bosphorus, is a 31 km long waterway that connects the Black Sea to the Sea of Marmara whereas the Strait of Çanakkale, also known as the Dardanelles connects the Sea of Marmara, to the Aegean Sea. These two waterways together with the Sea of Marmara are called the Turkish Straits and they provide a unique gateway from the Black Sea to the Mediterranean Sea, and

therefore to the est of the world. Bosphorus being the narrower one of the Turkish Straits has an average width of 1.5 kilometers whereas its minimum width is 700 meters. Each vessel passing through the Bosphorus must change its course 14 times where 4 of them require more than 45 degrees. As an addition to these geographic facts, surface currents up to 4 knots make the travel through the strait prone to casualties. More importantly, the Bosphorus lies along both sides of Istanbul, the largest city of Turkey with a population of 10 million (Figure 1). In November 1979, 29 Million gallons of oil spilled at Bosphorus due to a tanker accident. This shows that a vessel casualty in the future may cause a severe damage to the city.

Figure 1. Location Map of the Bosphorus and the City of Istanbul.

The traffic through the Bosphorus is very busy with vessels of both transit and local traffic. While in 1938 only 4500 vessels travelled through the Bosphorus, this number steadily increased to 50000 vessels in 1997. Among all the vessels passed through the Bosphorus in 1997, 4303 of them were oil tankers and 48 of them were longer than 150 m. Table 1 below summarises the casualties between 1982-1994 (Oğuzülgen, 1995)

Type	Number of vessels	Percent of vessels	Vessels with pilot	Caused pollution	Lost lives
Collision	168	57%	19	3	3
Grounding	65	22%	8	-	-
Stranding	24	8%	4	-	-
Fire	25	8%	4	-	1
Other	14	5%	5	-	7
Total	296	100%	40	3	4

Table 1. Vessel Casualties in Bosphorus between 1982 and 1994 (from Oğuzülgen, 1995).

2. Past Work

Although individually the existing knowledge on the physical and statistical aspects of the problem are well established a complete solution to the tanker casualty problem is not available. Most of the studies on modeling the casualties are based on statistical estimation methods and time-series analysis that utilise the past data. Some of these studies are found in econometric safety analysis literature.

Talley (1995) analyses the determinants of accident severity to evaluate the policies for reducing the vessel damage severity and the subsequent oil spillage of tanker accidents. Anderson and Talley (1995) uses a similar approach to study the determinants of the oil cargo spill, size of tanker and tanker barge vessel accidents. Cohen (1995) presents a market model to evaluate the economic losses of the 1989 Exxon Valdez oil spill. Le Blanc et. al. (1988) presents a regression model to estimate the vessel casualties depending on river stage, system usage rate, and weather. Le Blanc et. al. (1995) present a cluster analysis of vessel accidents on the lower Mississippi River.

The closest studies to the our problem are the ones developed by the United States Department of Transportation for the U.S. Coast Guard's Office of Navigation Safety and Waterway. Maio et. al. (1991) develop a regression model to estimate the waterway casualty rate depending on the type of waterway, average current velocity, visibility, wind velocity, length of primary traffic route, channel width, etc. Kornhauser and Clark (1995) use this regression model to estimate the vessel casualties resulting from additional oil tanker traffic through the Bosphorus.

We believe that methods based on statistical estimation are not adequate to assess the casualty risks due to two main reasons. First, the data collected over a time period at a given waterway cannot be used immediately to analyse the risks at another waterway since the physical forcing mechanisms, vessel traffic, etc. may be different. Second, if the vessel traffic is expected to increase rapidly in the near future, it is not possible to build a reliable estimation model based on the previous data since such a condition has not been observed in the past.

In this paper, we present a stochastic model that can estimate the vessel casualties from tanker traffic through a narrow waterway, such as the Bosphorus, the Dardanelles, the Houston Ship Channel, or the Suez Canal.

3. General Model

In the present study, a state-space representation of the waterway is developed to determine the location of vessels at a given time. Hydrodynamic forces, specifically the distribution of magnitude and direction of currents at a given location are used to update the original course of the vessel resulting in drift probabilities. These probabilities and random arrival of vessels are then incorporated into a Markov chain model. By analyzing the time-dependent probabilities of the Markov process, performance measures are obtained including the probability of casualty and the expected number of casualties. Figure 1 depicts the components of the analysis.

The model output includes risk charts indicating casualty probabilities across the geometry of the waterway at a given time and vessel intensity. Furthermore the model can be used to investigate the relationship between the vessel traffic intensity and global measures of casualty risk such as the expected number of casualties per vessel or per time.

The model operates in three building blocks (Figure 2). The first building block is the hydrodynamic model. The most important forcing mechanism that affects vessels travelling in a waterway is the surface current. This model determines the current velocity at a given location of the waterway depending on wind, channel geometry, bottom topography, and boundary conditions. In order to ensure numerical tractability, a waterway represented as a grid consisted of a finite number of elements. The first building block yields the current velocity in each of these elements.
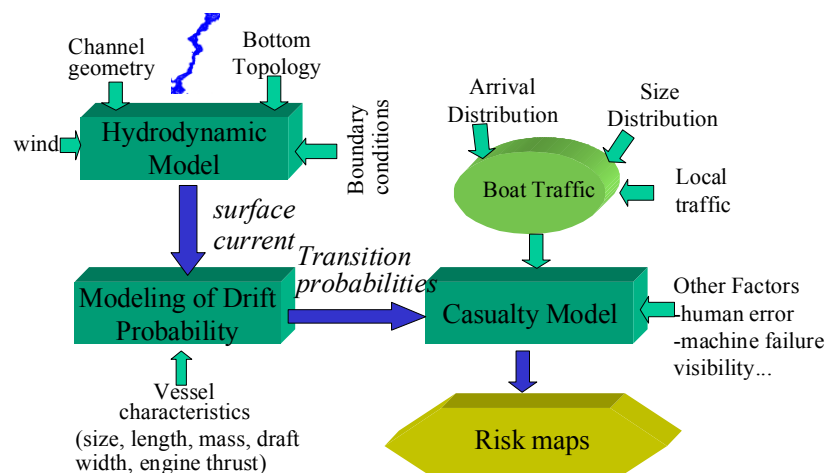

Figure 2. Components of the General Model

The second building block gives the drift probabilities for a vessel travelling at a given location of a waterway. Due to the surface current, the vessel may drift from its original route. This drift is one of the most important factors for vessel casualties along a waterway. Important parameters effecting the course drift are the hydrodynamic conditions and the vessel characteristics including size, length, draft, mass, engine thrust, etc. This building block first determines the distribution of drift from a vessel's original route and then discretize this distribution to three drift probabilities: (1) maintain the original course (2) drift to the right (3) drift to the left. For example, for a north bound vessel located at a certain grid, this model estimates the probabilities that there will be no drift, or a drift to the northwesterly or northeasterly grids during the next time step depending on the vessel and current characteristics in this grid.

The third building block is a state-space model of vessels travelling along a waterway. This model incorporates the drift probabilities obtained from the second building block, arrival distribution of the vessels, and other effect into a Markov chain model. By analysing the probability distribution of vessel positions in the waterway at a given time, the probabilities that an inter-vessel collision or grounding occurs place at a given location at a given time are derived. Finally, steady-state probability distributions and expected number of inter-vessel collisions, groundings, and total casualties are obtained. These results allow us to construct various risk charts. A major part of this paper is on the casualty model where operations research techniques have been used. In the next sections, we give more detailed information about these building blocks.

4. Hydrodynamic Model

The hydrodynamic model computes the current velocity depending on channel geometry, bottom topography, wind shear and boundary conditions as shown in Figure 3. We assume that the effect of currents on the vessel drift is more profound compared to other external forces in a narrow channel.
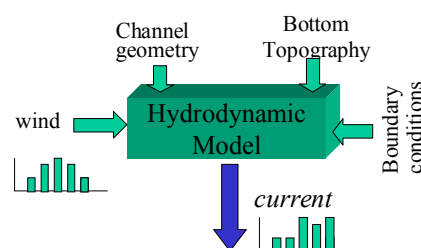

Figure 3. Hydrodynamic Model

The current circulation is governed by conservation of mass (Equations 1) and conservation of linear momentum (Equations 2,3). Using the appropriate boundary conditions, these equations are numerically solved to determine the current velocity at a given location of the channel. A finite element model developed by Thomas and McAnally, 1990 is used for the numerical solution. In our model the waterway is represented in a curvilinear grid.

$$\frac{\partial \eta}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial}{\partial x}(h+\eta) - \frac{\varepsilon_{xx}}{\rho}\frac{\partial^2 u}{\partial x^2} - \frac{\varepsilon_{xy}}{\rho}\frac{\partial^2 u}{\partial y^2} + \frac{1}{\rho h}\left(\tau_{sx} - \tau_{bx}\right) \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial}{\partial y}(h+\eta) - \frac{\varepsilon_{yx}}{\rho}\frac{\partial^2 v}{\partial x^2} - \frac{\varepsilon_{yy}}{\rho}\frac{\partial^2 v}{\partial y^2} + \frac{1}{\rho h}\left(\tau_{sy} - \tau_{by}\right) \tag{3}$$

where t is time, x, y are horizontal distances, g is gravitational acceleration, ρ is water density, h is water depth, η is water surface elevation, u, v are mean current velocities in x and y directions, τ_{sx}, τ_{sy} are surface wind stresses, τ_{bx}, τ_{by} are bottom shear stresses, and ε_{xx}, ε_{xy}, ε_{yx}, ε_{yy} are turbulent eddy viscosities.

Although channel geometry and bottom topography do not change with time, wind velocity and boundary conditions do. In order to incorporate the effect of wind velocity variability into our model, we first solve the finite element model for each occurrence of wind and boundary conditions deterministically and obtain the corresponding current circulation. By drawing wind and boundary condition realisations from their yearly distribution, we determine the approximate distribution of current circulation. Note that incorporating the variability of wind and boundary conditions directly into the equations to determine the current velocity and then solving the resulting stochastic differential equations directly yield the exact current distribution. However the latter method is numerically and theoretically intractable.

5. Modeling of Drift

After determining the distribution of current velocity, we analyse the effects of the current on the intended route of a vessel by incorporating the characteristics of the vessel into a drift model. We first derive the equations that yield the drift from a vessel's original route

depending of current velocity and characteristics of the vessel including its mass, length, draft, and engine thrust. Figure 4 shows the characteristics of a vessel, current, and drift.
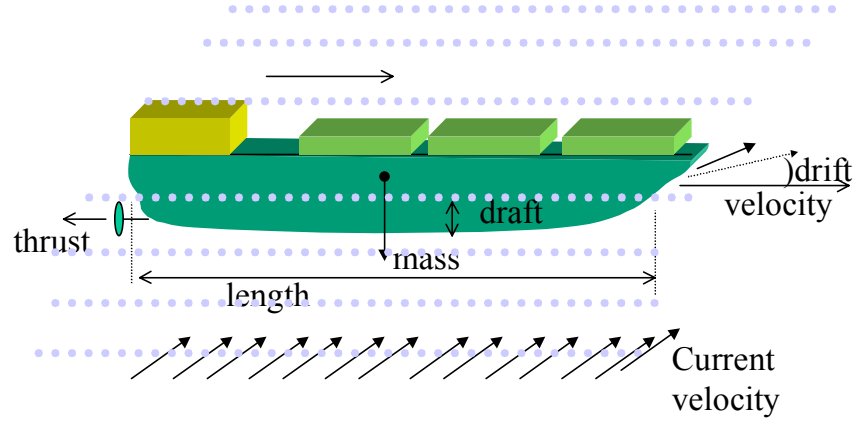

Figure 4. Modeling of Drift

Let $\Delta\gamma$ be the drift angle.

$$\Delta\gamma = \tan^{-1}(y/x) \tag{4}$$

Therefore the angular drift velocity ω is

$$\omega = \frac{d(\Delta\gamma)}{dt} \tag{5}$$

The sums of hydrodynamic forces acting on the ship in x- and y-directions, F_x and F_y, descibe the motion of a ship with mass m given as

$$m\frac{d^2x}{dt^2} = F_x \tag{6}$$

$$m\frac{d^2y}{dt^2} = F_y \tag{7}$$

The hydrodynamic force acting on the ship depends on the relative magnitude of the current and also on the cross sectional area of the ship:

$$F_x = \frac{1}{2}C\rho A_x |\vec{v}| v_x \tag{8}$$

$$F_y = \frac{1}{2}C\rho A_y |\vec{v}| v_y \tag{9}$$

where C is the hydrodynamic friction constant, ρ is the water density, A_x and A_y are projections of cross-sectional areas of the ship in contact with the current in x- and y-

directions. The length, width, and draft of a vessel are used to determine the cross sectional area of the ship in a given direction. In the above equation $\vec{v}$ is the relative current with respect to ship motion that can be expressed as

$$\vec{v} = v_x \vec{i} + v_y \vec{j} = (v_{x,c} - v_{x,s})\vec{i} + (v_{y,c} - v_{y,s})\vec{j} \qquad (10)$$

where $v_{x,c}$ and $v_{x,c}$ are current and $v_{x,s}$ and $v_{x,s}$ are ship velocities in *x*- and *y*-directions.

Successive substitution and simplification of the above equations yield a set of Riccatti-type nonlinear differential equations. In these equations, current velocity, length, mass, and draft are variable while engine thrust and therefore ship velocity is constant since vessels are required to travel with constant speed along a waterway. Length, mass, and draft of different vessels may vary randomly. Therefore, the drift velocity will be different for each vessel type and for each realisation of current velocity at a given location. Similar to the analytical simulation of the hydrodynamic model, incorporating this variability directly into the equations and then solving the stochastic nonlinear differential equations yield a more accurate distribution but it increases numerical calculations dramatically. Therefore to incorporate the variability in our model, we solve the above equations deterministically for each realisation of current velocity and vessel type and obtain approximate angular drift distribution by compiling the solutions of each realisation. After obtaining the angular drift distribution, we discretize the distribution into three drift probabilities that are used as state-transition probabilities in the Markov chain model. Figure 5 summarises the inputs and outputs of this building block.
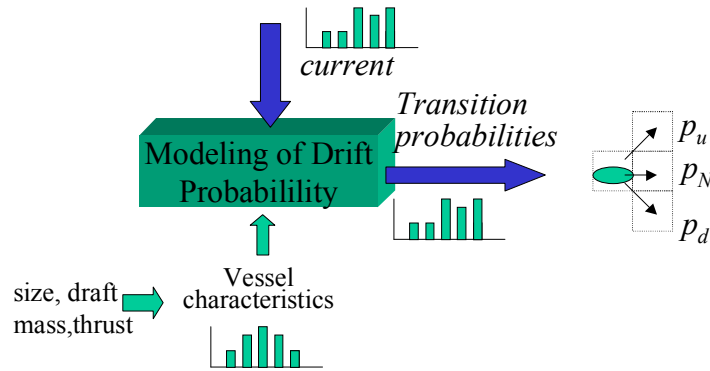

Figure 5. Modeling of Drift Probability

6. Modeling of Casualties

The last building block is a casualty model that incorporates drift probabilities, arrival distribution, and other effects into a Markov chain model. First, a state-space representation of the waterway is obtained. This is done by dividing each element of the grid used in the

hydrodynamic model into smaller sub-elements to increase the accuracy of vessel movements along the waterway. Second, we model the vessel traffic by analysing the travel of each vessel along the waterway as a random walk defined by the drift probabilities obtained. More specifically, we obtain the probability that a vessel is located at a given location of the waterway at a given time from the transient analysis of the Markov chain.

The two most important vessel casualties are grounding and collision. It is reported that 24.8% of oil spills from vessels (1960-1995) is due to "groundings" while 21% of oil spills from vessels (1960-1995) is due to "collisions" (Etkin, 1997). Therefore, only inter-vessel collision and grounding are modelled as possible casualties resulting from tanker traffic. The steady-state inter-vessel collision and grounding probabilities and also the expected number of inter-vessel collisions, groundings, and casualties in the long run are obtained. Risk maps and other risk charts are derived from the steady-state results. Figure 6 shows the components of the casualty model. Tan and Otay (1998) present an earlier version of the casualty model.
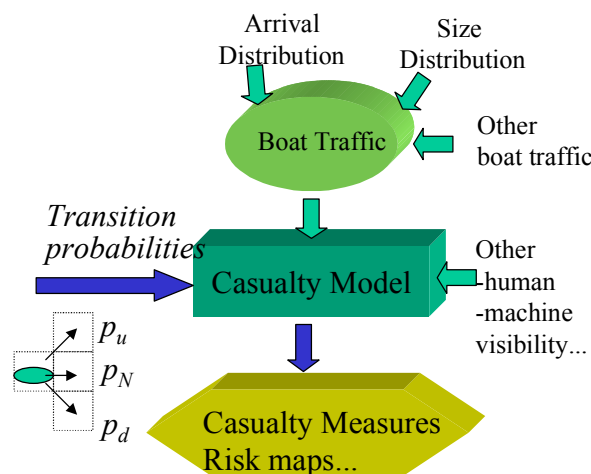

Figure 6. Modeling of Vessel Casualties

For the vessel traffic, we develop a model that can be used to estimate the locations of the vessels, and therefore, to determine the casualty probabilities conditioned on the current locations of vessels. This analysis can be used in traffic control in conjunction with a system that tracks the vessel in time and locates them at a given time.

The location of a vessel at time t is a random variable due to possible course deviations. We assume that movements of vessel along the waterway are independent of each other. Note that this is a simplifying assumption since vessels may alter their course temporarily to avoid

collision depending on the position of other vessels. Since this effect is included in the casualty model, we kept these movements independent to simplify the analysis.

7. Analysis of a Special Case

In this section, we analyse a special case in order to exploit the analytical results presented in the previous section. We consider a 100×10 rectangular grid. It is assumed that inter-vessel collision occurs when two vessels enter the same grid at the same time whereas a vessel may ground only at boundaries, i.e., at j=1 or j=10. A vessel may drift towards east with probability 0.1 and towards west with probability 0.1 when it is located in interior grids. When it reaches the grounding zone it stays there with probability 0.9 and returns to the interior region with probability 0.1. Vessels arrive with equal rates from North or from South and enter the waterway from the centre zone randomly. Figure 7 below shows the rectangular grid, arrival model, and casualties.
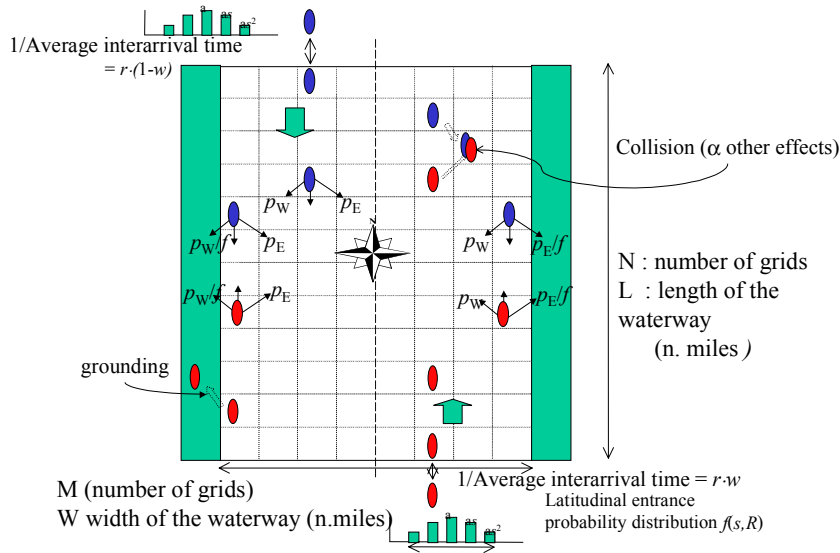

Figure 7. Modeling of vessel traffic and casualty

This special case can be solved semi-symbolically. The solution for the casualty probabilities and steady-state expected number of collisions and groundings are not given here for brevity. We investigate the effects of arrival rate of vessels, those of waterway length and width, and also the effects of drift probability. Figure 8 shows that the expected number of collisions and casualties increase quadratically with the arrival rate while the expected number of groundings is a linear function of the arrival rate.

As the waterway length increases, the model predicts that it is more likely that an inter-vessel collision or grounding takes place. As the waterway width increases, it is less likely that two vessels are located at the same place at the same time, thus the expected number of collision decreases. Similarly, as the waterway width increases, it is less likely that a vessel will drift from its intended route to reach the grounding zone and therefore the expected number of groundings also decreases. Finally, it is more likely that a vessel collides into another vessel or grounds if drifts away from its intended route.
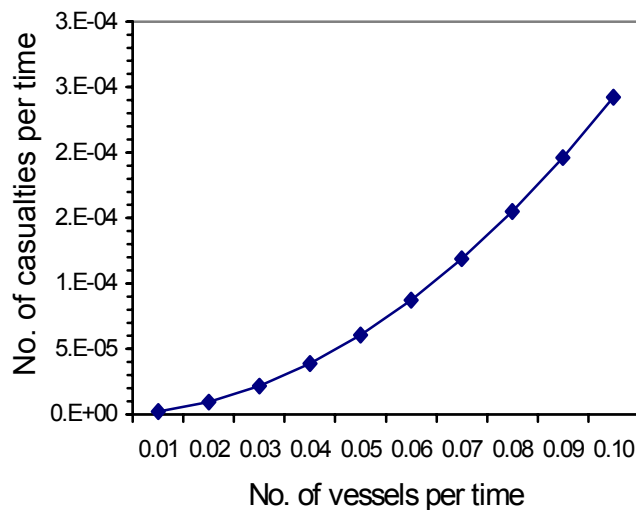

Figure 8. Effect of traffic intensity on vessel casualty

8. Conclusions

In this study, we present a Markov chain model to evaluate the vessel casualty risks resulting from tanker traffic through narrow waterways. As a contrast to previous studies based on statistical analysis of past data, the present model is based on modeling of physical forces and movements of individual ships. Therefore, this approach is geared towards explaining why vessels collide at a specific waterway at a specific time. The results can be used both in traffic control by tracking individual ships and using the transient analysis to estimate possible casualties and also in planning and policy development by focusing on steady-state behaviour.

Our general framework consists of three parts: Analysis, planning, and control. The present study constitutes the analysis part. Having the methodology to compute the probability of casualty, our future goal will be the minimisation of the collision risk by controlling the vessel traffic. Specifically, we will focus into real-time simulation of vessel traffic. That is, for known vessel positions, possibly using radar or geographical positioning systems, we can make

time projections for the expected vessel positions and take necessary precautions to minimise the risk of a potential casualty. Finally, if a casualty, especially an oil spill, occurs despite all the precautions, the rescue operations needs to be managed in the most effective way which will be incorporated in our future work.

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