A Simulation Study of the Accident Risk in the Istanbul Channel

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Abstract

Ships are prone to accidents in the Istanbul Channel, which has a considerable amount of naval traffic and is one of the most difficult-to-navigate waterways in the world. Such accidents impose risks on the nearby population, property, and the environment. Naturally, besides the adverse meteorological and geographical conditions, the increase in the volume of transit and local naval traffic has negative effects on these risks. The goal of this study is to investigate accident-prone conditions in the Channel through Bayesian analysis and simulation modeling. Bayesian analysis is applied to obtain estimates for conditional naval accident probabilities in the Channel (conditions considered corresponding to some suspected accident-causing factors, which can be routinely monitored and recorded over time). The simulation model developed takes into account the Channel characteristics and the critical traffic rules and behavior in the Channel, while deploying the conditional accident probabilities determined through the Bayesian method. As such, this model provides a platform for the analysis of various accident-causing factors and for scenario analysis.

1. Introduction

Although the sea is not a particularly risky mode of transport, accidents do happen in waterways. Furthermore, the transport of hazardous or dangerous substances by sea creates risks that are quite different from risks created by other modes of transport [12]. A tanker can carry 100,000 tons of flammable liquid, or 20,000 tons of liquefied natural gas, which implies that the impact zone in the case of a spill can be very large, and the undesirable consequences can be far reaching.

Ships spend most of their time in deep sea, where the population at risk is limited to the crew of the ship, and where the probability of collision with another ship is almost zero. However, when a ship is near land (and encounters heavy sea traffic), either for loading and unloading activities, or due to travel in a narrow waterway (such as the Istanbul Channel), the risks imposed on the population on land and the environment may become significant. For example, the US Coast Guard's Casualty Maintenance Database contains about 36,000 accident records for a set of 23 zones encompassing 82 deep draft ports in the U.S. over a 10-year period [12]. The majority of these accidents are minor. However, major accidents, such as the oil spill caused by Exxon Valdez (which cost the company over $3,500,000,000 in cleanup and compensation costs [2]) or the Independenta and Nassia accidents at the Istanbul Channel occur too frequently to ignore the risks associated with this mode of transport.

Naturally, transit and local sea traffic in the Istanbul Channel, which is one of the most difficult-to-navigate waterways in the world, carries some very serious risks for the city of Istanbul and the environment. (There were 157 collisions in the Istanbul and Dardanelles channels during 1988-1992 [8] and the EIA rates the possibility of accidental oil supply disruptions the greatest for supplies moving through these Channels [1]). These risks have the potential to cause loss of human life, environmental pollution, damage to historical and cultural heritage, and property damage in huge numbers and dimensions--through accidents, such as collision of vessels with each other or with the land mass bordering the Channel, leading to fires, explosions, poisonous gas releases, and sinkings. In parallel to the increases in the Channel traffic and the growth of the city, and related to the quantity and characteristics of the involved vessels, these accident risks have the potential to amplify in time.

The estimation of the underlying accident probabilities and the projection of the number, type, and location of potential naval accidents, in regard to, i) vessel characteristics and sea traffic density, ii) meteorological/environmental conditions, iii) Channel physical characteristics, and iv) traffic rules and risk mitigating measures, is a precondition for a thorough risk assessment in the Channel Region. Such an assessment will facilitate the determination and implementation of appropriate risk mitigating measures.

Considerable naval traffic, naval accident, and other data related to this issue have been assembled by various organizations and agencies over the years. Furthermore, it is perceived that, based on the available data, Bayesian analysis and simulation would be quite useful quantitative tools in the analysis of the above-mentioned accidents [6]. Within the study discussed in this paper, first data from different sources is compiled into a coherent and consistent set, then Bayesian analysis is applied to obtain estimates for conditional naval accident probabilities in the Istanbul Channel (conditions identified corresponding to the potential accidentcausing factors mentioned above). Finally, a simulation model of the naval traffic in the Channel, deploying these accident probabilities, is developed.

Simulation modeling of similar problems has been done in literature. One example is [4], which models ship collisions occurring while overtaking other ships in the Dover Strait; another example is the modeling of aircraft collisions [3]. Most of these researchers have also used various simplifying assumptions in order to be able to form analytical models.

2. The Determination of Conditional Accident Probabilities

Preliminary observations and interviews with experts have indicated that naval accidents in the Istanbul Channel are not purely random events, but rather highly influenced by various factors. The following characteristics and local conditions have been especially emphasised as possible accident-causing factors:

i) types and characteristics of the vessels passing through the Channel;

ii) the Channel naval traffic density;

iii) meteorological/environmental conditions (such as rain, wind, visibility, currents);

iv) the geographical characteristics of the Channel (such as width, number of bends, sharpness of bends).

The status of the above characteristics and conditions can be identified for most of the Channel naval accidents that have occurred in the past and furthermore some general information and classification is available for routine Channel transits (i.e., passages not involving naval accidents) regarding these characteristics and conditions. Accordingly, a quantification of the relationship between naval accident probabilities and these factors, based on Bayesian Methods, is deemed appropriate.

The "Bayes" formula defines the probabilistic relationship between some dependent events as

$$P(A/B)=\frac{P(B/A)*P(A)}{P(B)}$$

where, P(A/B) is the conditional probability of the occurrence of event "A" given that event B has occurred;

P(B/A) is the conditional probability of the occurrence of event "B" given that event A has occurred;

P(B) is the probability of the occurrence of event "B";

P(A) is the probability of the occurrence of event "A."

In this study, "event A" corresponds to "a particular type of naval accident" and "event B" corresponds to "a specific realization of the set of accident causing factors considered". Different types of accidents have been aggregated into two general classes:

i) Collisions (CL): These accidents involve the collision of moving transit vessels;
ii) Other accidents (OT): This class includes accidents such as grounding of a vessel, ramming of a vessel with the shoreline or another vessel at anchor, fire or leakage in a vessel, collision between a transit vessel and a local/cross traffic vessel.

Possible accident-causing factors considered are:

- Various characteristics of transit vessels such as
  - **L_i:** Length of transit vessel "i";
  - **T_i:** Type of transit vessel "i";
  - **F_i:** Flag of transit vessel "i";
- Local meteorological conditions such as
  - **V_i:** Visibility at the Channel at time of passage of transit vessel "i";
  - **W_i:** Wind speed in the Channel at time of passage of transit vessel "i";
- Geographical characteristics and local traffic density of different Channel sections such as
  - **Z:** Zone (region) of the Channel a transit vessel is passing through.

The reason length and type of a naval vessel are considered as potential accident-causing factors is obvious: the longer a vessel, the more difficult it becomes to navigate in narrow waterways, such as the Istanbul Channel, and certain types of ships are more prone to accidents than others because of their design, cargo, and technical capabilities. Furthermore, experts have indicated that the physical conditions of a vessel, such as its age and maintenance level, play a major role in its safe passage through the Channel. Unfortunately, these characteristics have not been recorded for many of the ships that were involved in past accidents, and they are simply not available for vessels that have made routine Channel transits. On the other hand, many experts have hinted that there is a high correlation between the physical condition of a transit ship and the flag it is carrying. Therefore, the flag of a transit vessel is considered in this study as a proxy indicator for the physical conditions of that ship.

The reason visibility and wind speed in the Channel are considered as potential accident-causing factors is also obvious: the lesser the visibility and the greater the wind speed, the more difficult it becomes to navigate a naval vessel in this narrow waterway.

The geographical characteristics of the Istanbul Channel, such as its width, sharpness, frequency of its bends, and its currents and cross currents, vary considerably throughout its 31-km. length. Furthermore, the level of local naval traffic (i.e., cross traffic moving people and goods between the two shores of the Channel and the local fishing or pleasure boats) also varies throughout the length of the Channel. All of the mentioned factors influence Channel navigation and may be considered as potential accident-causing factors. In this study, the Channel is divided into 7 distinct regions (zones) to account for the variances in these factors, and in each zone their aggregate effect on accident probabilities is pursued.

Accordingly, the conditional probability of an individual transit vessel "i" being involved in an "OT" class accident in section "j" of the Channel, given that its flag code is k_1, its length class is k_2, its type code is k_3, visibility level and wind speed at the time of its passage are k_4 and k_5 respectively, may be written as,

$$P\left\{ {OT_i}\Big/ {F_i=k_1, L_i=k_2, T_i=k_3, V_i=k_4, W_i=k_5, Z=j} \right\} = \frac{P\left\{ {F_i=k_1, L_i=k_2, T_i=k_3, V_i=k_4, W_i=k_5, Z=j}\Big/ {OT_i} \right\} * P\{OT_i\}}{P\{F_i=k_1, L_i=k_2, T_i=k_3, V_i=k_4, W_i=k_5, Z=j\}} \qquad (1)$$

Similarly, the conditional probability of an individual transit vessel "i" being involved in an "CL" class accident in section "j" of the Channel, given that its flag code is k_1, its length class is k_2, its type code is k_3, visibility level and wind speed at the time of its passage are k_4 and k_5 respectively, may be written as,

$$P\left\{ CL_i \middle/ F_i = k_1, L_i = k_2, T_i = k_3, V_i = k_4, W_i = k_5, Z = j \right\} = \frac{P\left\{ F_i = k_1, L_i = k_2, T_i = k_3, V_i = k_4, W_i = k_5, Z = j \middle/ OT_i \right\} * P\{CL_i\}}{P\{F_i = k_1, L_i = k_2, T_i = k_3, V_i = k_4, W_i = k_5, Z = j\}} \tag{2}$$

In this form, past data may be deployed in estimating conditional naval accident probabilities. However, the joint conditional probability functions,

$$P\{F, L, T, V, W, Z / OT\}\ ;\ P\{F, L, T, V, W, Z / CL\}$$

and the joint probability function,

$$P\{F, L, T, V, W, Z\}$$

would still be difficult to handle with respect to data needs and functional form without additional independence properties. The independence of {F, L, T}, {V, W} and {Z} from one another can easily deducted, since the first set is related to the passing vessels, the second set to meteorological conditions, and the third to locations in the Channel (meteorological conditions do not vary along the Channel, every transit vessel passes through the full length of the Channel and meteorological conditions do not influence the profile of vessels entering the Channel). On the other hand, the following independence assumptions cannot be taken for granted; nevertheless, a pre-analysis of the past naval traffic and accident data indicate that they could be undertaken without a major loss of accuracy.

i) {F}, {L}, and {T} are mutually independent;
ii) {F/OT}, {L/OT}, {T/OT}, {V,W/OT}, {Z/OT} are mutually independent
iii) {F/CL}, {L/CL}, {T/CL}, {V,W/CL}, {Z/CL} are mutually independent.

These independence properties simplify equation (1) into,

$$P\left\{ OT_i \middle/ F_i = k_1, L_i = k_2, T_i = k_3, V_i = k_4, W_i = k_5, Z = j \right\} =$$

$$\frac{P\left\{ F_i = k_1 \middle/ OT_i \right\} P\left\{ L_i = k_2 \middle/ OT_i \right\} P\left\{ T_i = k_3 \middle/ OT_i \right\} P\left\{ V_i = k_4, W_i = k_5 \middle/ OT_i \right\} P\left\{ Z = j \middle/ OT_i \right\} P\{OT_i\}}{P\{F_i = k_1\} * P\{L_i = k_2\} * P\{T_i = k_3\} * P\{V_i = k_4, W_i = k_5\} * P\{Z = j\}}$$

or equivalently,

$$\frac{P\left\{ F_i = k_1 \middle/ OT_i \right\}}{P\{F_i = k_1\}} x \frac{P\left\{ L_i = k_2 \middle/ OT_i \right\}}{P\{L_i = k_2\}} x \frac{P\left\{ T_i = k_3 \middle/ OT_i \right\}}{P\{T_i = k_3\}} x \frac{P\left\{ Z = j \middle/ OT_i \right\}}{P\{Z = j\}} x \frac{P\left\{ V_i = k_4, W_i = k_5 \middle/ OT_i \right\} P\{OT_i\}}{P\{V_i = k_4, W_i = k_5\}} \tag{3}$$

Similarly, it can be shown that (2) is equivalent to,

$$P\left\{ CL_i \middle/ F_i = k_1, L_i = k_2, T_i = k_3, V_i = k_4, W_i = k_5, Z = j \right\} =$$

$$\frac{P\left\{ F_i = k_1 \middle/ CL_i \right\}}{P\{F_i = k_1\}} x \frac{P\left\{ L_i = k_2 \middle/ CL_i \right\}}{P\{L_i = k_2\}} x \frac{P\left\{ T_i = k_3 \middle/ CL_i \right\}}{P\{T_i = k_3\}} x \frac{P\left\{ Z = j \middle/ CL_i \right\}}{P\{Z = j\}} x \frac{P\left\{ V_i = k_4, W_i = k_5 \middle/ CL_i \right\} P\{CL_i\}}{P\{V_i = k_4, W_i = k_5\}} \tag{4}$$

Each of the individual probability or conditional probability terms in equations (3) is estimated based on past data (of the 1980-1997 period) as follows.

$P\{F=k_1/OT\}$: This term reflects the probability of a transit vessel to have flag k1, given that it is involved in an accident in the accident class "OT". It is estimated by the

	frequency of flags k1 in the past "OT accidents" (i.e. dividing the total number of vessels of flag k1 involved in "OT accidents" to the total number of vessels involved in "OT accidents").
$P\{L=k_2/OT\}$:	This term reflects the probability of a transit vessel to have length class k2, given that it is involved in an accident in the class "OT". It is estimated by dividing the total number of vessels of length class k2 involved in "OT accidents" to the total number of vessels involved in "OT accidents".
$P\{T=k_3/OT\}$:	This term reflects the probability of a transit vessel to have type code k3, given that it is involved in an accident in the class "OT". It is estimated by dividing the total number of vessels of type code k3 involved in "OT accidents" to the total number of vessels involved in "OT accidents".
$P\{Z=j/OT\}$:	This term reflects the probability of a transit vessel to have an OT accident in zone j, given that it is involved in an accident in the class "OT". It is estimated by dividing the total number of OT accidents in zone j to the total number of accidents in the class OT.
$P\{V=k_4, W=k_5/OT\}$:	This term reflects the probability of visibility being k4 and wind speed being k5, given that an accident in the class "OT" has occurred. It is estimated by dividing the total number of days in which there has been an OT accident while the visibility was k4 and wind speed was k5 to the total number of days in which there has been an OT accident.
$P\{OT\}$:	This term reflects the probability of a transit vessel to have an accident in the class "OT". It is estimated by dividing the total number of vessels involved in OT class accidents in the Channel passages over the period 1980-1997 to the total number of transits in the same period.
$P\{F=k_1\}$:	This term reflects the probability of a transit vessel to have flag k1. It is estimated by the frequency of flags k1 in all the Channel passages over the period 1980-1997. (i.e., dividing the total number of transit vessels of flag k1 to the total number of all transit vessels).
$P\{L=k_2\}$:	This term reflects the probability of a transit vessel to have length class k2. It is estimated by dividing the total number of transit vessels of length class k2 to the total number of all transit vessels.
$P\{T=k_3\}$:	This term reflects the probability of a transit vessel to have type code k3. It is estimated by dividing the total number of transit vessels of type code k3 to the total number of all transit vessels.
$P\{Z=j\}$:	This term reflects the probability of a transit vessel to pass through zone j. By definition it is unity.
$P\{V=k_4, W=k_5\}$:	This term reflects the probability of visibility being k4 and wind speed being k5 on any given day. It is estimated by dividing the total number of days in which the visibility has been k4 and wind speed has been k5 to the total number days in the 1980-1997 period.

The conditional probability terms in equations (4) are also estimated in a similar fashion.

3. The Channel Naval Traffic Simulation Model

3.1 Model Development

Interviews with experts have indicated that the flow of transit traffic in the Channel is guided by a few clear and simple rules and is therefore quite suitable to be represented by a simulation model (the flow of local traffic on the other hand is far more erratic and complex due to the unpredictable behavior of many small craft). Furthermore, the past naval traffic and accident data regarding the Channel transit traffic is quite extensive, and the conditional accident probabilities associated with each individual transit vessel can be estimated as described in the previous section. These observations have led to the construction of the Istanbul Channel Naval Traffic Simulation Model (NTSM) based on the following principles:

i) Each transit ship arriving at either entrance of the Channel is to be individually represented and tracked in the NTSM;

ii) Local traffic is not tracked on individual vessel basis, rather it is represented as a "density" factor varying throughout the Channel. The local traffic density is expected to have a negative effect on naval accident probabilities of transit vessels (i.e., the larger the local traffic density in any given region of the Channel, the larger the accident probability in that region); such a correlation between the local traffic density and naval accidents has actually been demonstrated by earlier studies [6, 9, 10].

iii) There is a single southbound and a single northbound transit traffic lane in the Channel. Each lane is about 100 meters wide with the southbound lane located on the west of the northbound lane. These traffic lanes, whose bends follow the general profile of the Channel shoreline, are displayed in figure 1. Transit ships are not allowed to overpass one another, nor to deviate from their assigned lanes. All transit ships have a constant speed of 12 knots during their passage through the Channel (the speed is lowered to 6 knots if the weather conditions are unfavorable). Both lanes are open to international and national traffic from 6 a.m. to 10 p.m., unless the weather conditions are extremely unfavorable or a major accident has occurred. The traffic lane structure and rules described actually provide a quite realistic representation of the real situation.

iv) It is assumed that transit vessels arrive at the north and south entrances of the Channel one at a time and according to two identical independent exponential distributions (whose parameters are based on historical data). The type, length, and flag of arriving transit vessels are randomly determined according to empirical probability distributions obtained from historical data. Since time of passage is not recorded in historical data, the exponentiality assumption could not be extensively tested. However, tests with a few days data collected during the current study have provided positive results.

v) The Channel is divided into 8 regions and every transit vessel that enters the Channel from one entrance passes through all Channel regions to exit from the other end.

vi) Two different seasons are assumed. For each season, daily wind and visibility conditions are randomly determined according to empirical probability distributions obtained from the past frequencies of the wind and visibility conditions in that season. Each wind and visibility condition generated is assumed to hold over the whole Channel for the full duration of the day.

The NTSM is developed in the Visual Simulation Environment (VSM) simulation language [11]. In this model the wind and weather conditions of each day considered are generated as described in (vi) above, then transit vessels of that day are generated according to principle (iv) above. The vessels generated at the northern entrance of the Channel are assigned to the southbound lane and are moved southward, while the vessels generated at the southern entrance of the Channel are assigned to the northbound bound lane and are moved northward. The movement of the vessels resembles the movement of pieces on a checker board and the passage of time is synchronized with the set speed of the Channel naval traffic with respect to the prevailing weather conditions. However, before moving a vessel to the neighboring (southward or northward) cell, whether that vessel is involved in an OT class accident or not, its current location is randomly determined based on the conditional OT class accident probability of transit vessels, given the vessel's flag, length, type, location, and prevailing wind, visibility conditions. Furthermore, whenever two transit vessels moving in opposite directions cross each other, whether they are involved in an CL class accident or not, that point is also randomly determined based on the conditional CL class accident probability of transit vessels, given the vessel's flag, length, type, location, and prevailing wind, visibility conditions. Each OT and CL class accident is recorded together with its date, time, location, prevailing weather conditions, and characteristics of the vessels involved. The number and characteristics of transit vessels making safe passage are also recorded.

The NTSC also enables the users to view, on a map of the Istanbul Channel at the computer screen, the movements of the sea vessels and the related accidents within the Channel, in the desired detail and time period, at normal pace or with a speeded-up clock.

3.2 Model Validation

The validation of the model is achieved by comparing the simulation output for the 1980-95 period, with the historical data of the same period. The pairwise comparisons undertaken are:

i) The total number of OT and CL class accidents;
ii) The total number of OT and CL class accidents in each zone;
iii) The total number of OT and CL accidents for each flag;
iv) The total number of OT and CL accidents for each vessel type;
v) The total number of OT and CL accidents for each vessel length class;
vi) The total number of overall and individual flag transits;
vii) The total number of transits for each vessel type.

In each of these cases, first respective graphs are visually inspected, then the null hypotheses,

H_{01}: Number of OT accidents in hist. data = Number of OT accidents in sim. output

H_{02}: Number of CL accidents in hist. data = Number of CL accidents in sim. output

are statistically tested against,

H_{11}: Number of OT accidents in hist. data ? Number of OT accidents in sim. output

H_{12}: Number of CL accidents in hist. data ? Number of CL accidents in sim. output

The results of the tests have been satisfactory in almost all of the cases.

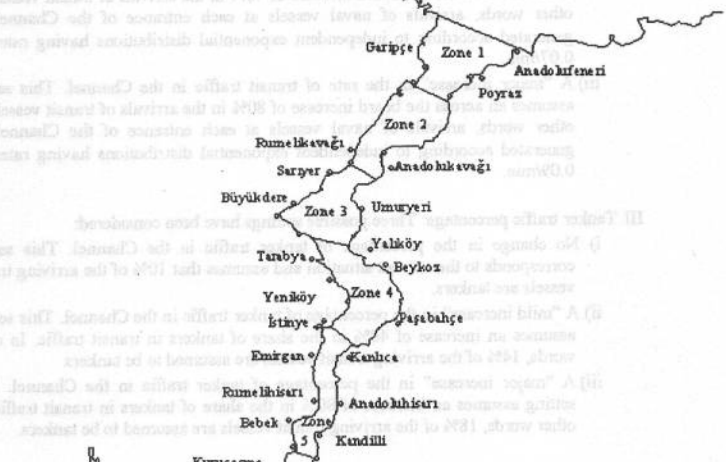

Figure 1. The Istanbul Channel and Its 8 Regions

3.3 Simulation Scenarios

Various simulation scenarios have been generated by assuming different settings of the considered potential accident-causing factors. Each such scenario can be described by the selected setting of the following factors:

I. Meteorological conditions: Two possible settings have been considered:
   - i) Summer conditions, where daily wind and visibility conditions are randomly generated using the empirical probability distribution obtained from the realized Channel wind-visibility conditions of the past 7 years' May-October period.
   - ii) Winter conditions, where daily wind and visibility conditions are randomly generated using the empirical probability distribution obtained from the realized Channel wind-visibility conditions of the past 7 years' December-March period.

II. Transit traffic rate: Three possible settings have been considered:
   - i) No increase in the rate of transit traffic in the Channel. This setting corresponds to the current situation and assumes no change in future transit traffic density. Arrivals of naval vessels at each entrance of the Channel are generated according to independent exponential distributions having rates $\lambda = 0.05$ per minute.
   - ii) A "mild increase" in the rate of transit traffic in the Channel. This setting assumes an across the board increase of 40% in the arrivals of transit vessels. In other words, arrivals of naval vessels at each entrance of the Channel are generated according to independent exponential distributions having rates $\lambda = 0.07$/min.
   - iii) A "major increase" in the rate of transit traffic in the Channel. This setting assumes an across the board increase of 80% in the arrivals of transit vessels. In other words, arrivals of naval vessels at each entrance of the Channel are generated according to independent exponential distributions having rates $\lambda = 0.09$/min.

III. Tanker traffic percentage: Three possible settings have been considered:
   - i) No change in the percentage of tanker traffic in the Channel. This setting corresponds to the current situation and assumes that 10% of the arriving transit vessels are tankers.
   - ii) A "mild increase" in the percentage of tanker traffic in the Channel. This setting assumes an increase of 40% in the share of tankers in transit traffic. In other words, 14% of the arriving transit vessels are assumed to be tankers.
   - iii) A "major increase" in the percentage of tanker traffic in the Channel. This setting assumes an increase of 80% in the share of tankers in transit traffic. In other words, 18% of the arriving transit vessels are assumed to be tankers.

IV. Large vessels percentage: Two possible settings have been considered:
   - i) No change in the distribution of vessel size within the transit traffic in the Channel. This setting corresponds to the current situation.
   - ii) A "tendency" towards larger transit vessels in the Channel. This setting assumes an increase in the share of larger vessels in transit traffic. Shares of vessels longer than 250 m. and of vessels in the 200-250-m. range are assumed to grow by 100%, to 5%, and 2% of the total respectively. Shares of vessels in the 150-200-m. range are assumed to grow by 50%, to 15% of the total.

V. Flags percentage: One possible setting has been considered:
   - i) No change in the distribution of vessel flags within the transit traffic in the Channel. This setting corresponds to the current situation.

VI. Local traffic density: Three possible settings have been considered:

i) No increase in the Channel local traffic density. This setting corresponds to the current situation and assumes no change in future local traffic density.

ii) A "mild increase" in the Channel local traffic density. This setting assumes an increase of 40% in the Channel local traffic density.

iii) A "major increase" in the Channel local traffic density. This setting assumes an increase of 80% in the Channel local traffic density.

Of the above mentioned settings, the combination I-i, II-i, III-i, IV-i, V-i, VI-i is called the base scenario and corresponds to the current situation in the Channel under "mild weather" conditions. All other scenarios are compared against this base scenario.

3.4 Treatment of Local Traffic Density in the Simulation Scenarios

Actually, "local traffic density" is the only one of the considered possible accident-causing factors that is not directly represented in the simulation model. Rather, its effects on naval accidents are indirectly considered within the conditional probability terms, P{Z=j/OT} and P{Z=j/CL}. So, case (VI-i) above, which corresponds to the current situation, is accounted for by deploying an empirical probability distribution obtained from historical data.

The treatment of cases (VI-ii) and (VI-iii) are somewhat more roundabout: It has been shown in [6, 10] that, in the Istanbul Channel, there is a direct correlation between the number of accidents and two potential accident-causing factors: local traffic density and severity of bends. Actually, the following functional relationship has been generated in the mentioned study.

$$\mathbf{A} = 13.307 + 0.23 * \mathbf{TD} + 0.593 * \mathbf{CT} \tag{5}$$

where, for each region of the Channel,

A represents the expected total number of accidents in that region of the Channel, over a period of 13 years;

TD represents the total number of turning degrees a typical transit vessel has to execute in order to stay in its allocated lane;

CT represents the cross traffic density resulting from the local ferry traffic in the region.

According to equation (5), assuming that all other related factors remain unchanged, a unit increase in Channel traffic density (whose current value ranges between 0 and 40 vessels per Channel mile, depending on the considered region) is expected to lead to 0.59 naval accidents over a period of 13 years. So, the conditions described in case (VI-ii) are fabricated by estimating the conditional probability terms P{Z=j/OT} and P{Z=j/CL} corresponding to this "mildly denser local traffic environment" as follows:

- increasing the CT values of all regions by 40%;
- obtaining an estimate for the annual number of accidents in each region through eq. (5);
- estimating P{Z=j/OT} and P{Z=j/CL} by dividing the estimates for the annual number of naval accidents in each region, with the current number of annual Channel transits.

The "highly denser local traffic environment" conditions described in case (VI-iii) are fabricated in a similar fashion (CT values of all regions are increased by 80% in this case).

3.5 Model Results

Due to experimentation time limitations, each scenario is run for a duration of 300 days. As expected, an increase in number of naval accidents is observed in most of the scenarios having higher transit traffic rates, denser local traffic conditions, higher percentage of longer ships, and/or adverse weather conditions. In mild weather conditions, the influence of higher transit traffic rate seems to be the largest; while in adverse weather conditions a denser local traffic environment seems to have the most negative effect.

The locations of the accidents and the characteristics of the vessels involved in accidents reveal some interesting insights regarding the occurrence of real naval accidents. Especially collisions seem to be concentrated in regions 7 and 8, where the local traffic density is much higher. As the population, as well as economic, social, and industrial activity in the Channel area increase, the local traffic density will also increase, especially in these regions close to the "downtown" area; and this will bring about seriously increasing risks to these extensively urbanized, high population regions. While vessel length does not seem to be an influential factor in mild weather conditions, frequency of longer vessel accidents seems to be increasing in adverse weather conditions. Similarly, frequency of tanker accidents seems to increase in adverse weather conditions and/or denser local traffic conditions; and the situation becomes especially worrisome when a higher tanker percentage is assumed together with adverse weather conditions and/or denser local traffic conditions.

Finally, the nightmare scenario, where a major increase in transit traffic rate, a major increase in local traffic density, adverse weather conditions, a tendency towards larger vessels, and a major increase in tanker traffic percentage are jointly assumed, deserves specific attention. In this scenario, around a 250% increase in collisions and a 200% increase in other accidents is predicted, while, not surprisingly, the accident concentration is in the critical regions 7 and 8. Since the basic parameters of this scenario could well be realized in the not too distant future, measures to improve the odds of safe passage through the Channel are fast becoming an absolute necessity for the city and inhabitants of Istanbul.

4. Conclusions and Suggestions for Future Work

This study has focused on potential naval accidents in the Istanbul Channel involving transit vessels. The relationship between such accident possibilities and some suspected accident-causing factors--such as length, type, and flag of transit vessels, wind, and visibility conditions at time of passage, Channel geographical conditions and local traffic density--has been quantified in terms of conditional accident probabilities, conditioned on the mentioned factors. Bayesian analysis has been applied on the past Channel naval traffic and accident data in order to determine these probabilities. Then, a simulation model has been developed, which takes into account the Channel characteristics and the critical traffic rules and behavior in the Channel, while deploying these conditional accident probabilities.

Due to time limitations, extensive testing with the simulation model has not yet been completed. However, even the preliminary results lead to some interesting observations. These observations, which are summarized in the previous section, highlight the influence of transit traffic rate, local traffic density, weather conditions, and some vessel characteristics on Channel naval accidents. This study contains no damage assessment regarding these accidents. However, since accident location, vessel type, vessel size, wind-visibility conditions, and a rough accident classification accompanies each naval accident registered in the simulation runs, the results obtained in this study could well qualify to be a good starting point for an extensive damage and risk assessment of the Istanbul Channel naval traffic. Furthermore, the appalling increase in accidents in some scenarios, whose basic parameters could well be realized in the future, clearly confirm the need for additional studies and measures to improve the odds of safe passage through the Channel.

No Quantitative Risk Assessment (QRA) study can be claimed to be perfectly accurate due to the uncertainties in the events involved. However, QRA is rapidly becoming a widely used and accepted way of quantifying risks associated with hazardous activities. A QRA study, taking into account the results generated in this study, will provide a defensible and rational tool for the estimation of naval transport risks in the Istanbul Channel. The relations between the assumptions, data, and results will be clear to anyone who is interested in studying such a QRA process and the developed models. Hence, the models will not only provide an objective framework for the assessment of existing and future risks, but also establish a rational basis for discussion of political decisions.

Another high-priority issue regarding any further quantitative analysis of Istanbul Channel naval traffic and its risks is proper data collection and storage. Within this context, detailed, periodic and current visibility and wind measurements, detailed and reliable recording of transit traffic data and pilotage services accomplished, and precise and full information regarding accidents and near accidents are strongly suggested.

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