RISK ANALYSIS OF THE TRANSIT VESSEL TRAFFIC IN THE STRAIT OF ISTANBUL

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Abstract

In this manuscript, development and preliminary results of a simulation based risk modeling study for the Strait of Istanbul is presented. The goal of this research is to analyze the risks involved in the transit vessel traffic in the Strait of Istanbul. In the first step of the study, the transit vessel traffic system in the Strait of Istanbul has been investigated and a simulation model has been developed. The model involves traffic rules and regulations, transit vessel profiles/schedules, pilotage/tugboat services, local traffic, meteorological and geographical conditions.

Regarding risk assessment, two sets of factors are used to evaluate the risk of accident in the Strait: the probability of an accident and its potential consequences, as estimated and evaluated at various points along the Strait. Experience has shown that maritime accident occurrences can be very dissimilar from one another and therefore, probabilistic analysis of accidents should not be done independent of the factors affecting them. Thus, in this study, we have focused on the conditional probability of an accident, under a given setting of various accident causing factors, estimated via subject-expert opinion. Assessment of the consequences of a given accident (in terms of its effects on human life, traffic efficiency, property and environment) is also accomplished using a similar approach.

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Finally, by integrating these assessments into the developed simulation model, the risks observed by each vessel at each risk slice are calculated in regard to the natural and man-made conditions surrounding. A scenario analysis is performed to evaluate the characteristics of the accident risk as the vessel moves along the Strait. This analysis allows us to investigate how various factors impact risk. These factors include vessel arrival rates, scheduling policies, pilotage service, overtaking and pursuit rules, and local traffic density. Policy indications are made based on the results of these scenarios.

1 Introduction

The Turkish Straits, which consist of the Straits of Istanbul and Çanakkale and the Sea of Marmara, have for centuries been one of the world's most strategic waterways since they constitute the Black Sea's sole maritime link to the Mediterranean and the open sea beyond. As such, they are a vital passageway not just for trade but for the projection of military and political power, while their extreme narrowness, winding contours and densely populated shores make navigation quite treacherous in these waterways.

The Strait of Istanbul is 31 km long, with an average width of 1.5 km and a mere 660m at its narrowest point [Wikipedia, 2008]. It has many sharp turns, forcing vessels to alter course (up to 80°) at least 12 times. Navigation is particularly treacherous at the narrow and winding regions, as vessels approaching from opposite directions cannot see each other around the bends.

Figure 1 The Strait of Istanbul

In addition to its winding contour, the unpredictable countervailing currents that may reach 7 knots pose significant danger to vessels. Surface currents in the Strait run from the Black Sea to the Sea of Marmara, while subsurface currents, 50 feet below the surface, run in the opposite direction. Within bays and near point bars, these opposing currents lead to turbulence. The unpredictable climate brings about further hazards. During storms with strong southerly winds, the surface currents weaken or reverse in some places, making it even harder to navigate. All these elements has the potential to cause vessels transiting the Strait to veer off course, run aground or collide, especially when combined with some human error and/or equipment failure.

The legal framework of vessel transit through the Strait of Istanbul is governed by the 1936 Montreux Convention [Montreux Conv., 1937]. When the Convention was put in place, less than 5,000 vessels passed through the Strait annually, whereas today, changes in the global shipping patterns have led to a ten-fold increase in the maritime traffic through the Strait. Many reasons have contributed to this immense increase. The Turkish Straits provide the only maritime link between the Black Sea riparian states and the Mediterranean, forcing these states to rely heavily on the Straits for foreign trade. The opening of the Rhine-Danube canal has linked the North and the Black Seas. Traffic originating from the Volga-Baltic and Volga-Don waterways has also increased in the recent years.

Still, the most alarming increase in traffic is observed in the number of vessels carrying dangerous cargoes. Since 1991, a considerable percentage of the oil and gas from the newly independent energy-rich states along the Caspian Sea reach the global markets through the Turkish Straits. The maritime traffic will increase substantially since the production is expected to double by 2010. In addition, Russian oil companies are setting ever higher targets for production and export. Analysts predict that Russia could be pumping 10 million barrels of crude oil daily by the end of the decade, a significant portion of which is expected to pass through the Straits.

During the 1930s, when the Montreux Convention went into force, transport of hazardous materials posed little concern due to the infrequent passages and small vessel sizes. However, the increases in traffic and vessel sizes have raised the likelihood and the severity of accidents. The unusual characteristics of the Strait and its climate, coupled with the failure to request pilotage in this treacherous waterway, have led to over 200 accidents in the past decade.

Major hazardous cargo accidents since 1960 are as follows. In 1960 the Greek-flagged M/T World Harmony collided with the Yugoslavian-flagged M/T Peter Zoranic, leading to the death of 20 crew members, severe oil pollution and fire that lasted several weeks, suspending the transit traffic. In 1979, Romanian-flagged Independenta and the Greek freighter M/V Evriyalı collided at the southern entrance of the Strait. 43 crew members died, 64,000 tons of crude oil spilled into the sea and 30,000 tons burned into the atmosphere. In yet another catastrophe, the Greek Cypriot vessels M/T Nassia and M/V Shipbroker collided in the Strait. 29 officers and crewmen perished and 20,000 tons of crude oil burned for five days, suspending the traffic for a week. A potential disaster was averted only because the accident occurred just north of the highly populated regions. In 2002, Maltese-flagged M/V Gotia ran into a pier in the Strait, spilling 18 tons of oil [Turkish Maritime Pilots, 2005].

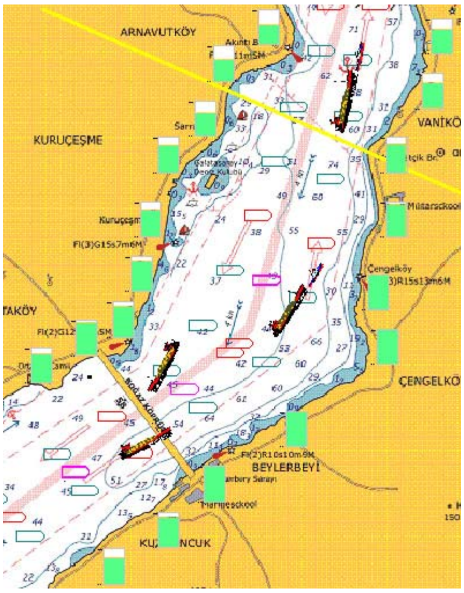
In order to ensure the safety of navigation, life, property and to protect the environment, the Turkish State unilaterally adopted in 1994 (and later revised in 1998) the Maritime Traffic Regulations for the Turkish Straits and Marmara Region [Official Gazette, 1994, 1998]. These regulations include extensive provisions for facilitating safe navigation through the Straits in order to minimize the likelihood of accidents and adverse consequences. The provisions aim to monitor vessels with hazardous cargoes, regulate the flow of vessel traffic by establishing new procedures for transit in the Straits, and attempt to account for dangerous meteorological and oceanographic conditions by restricting traffic under certain situations.

Although the adoption of new regulations and the accompanying additional safety precautions have decreased the danger, accidents still happen. The vulnerability of the Straits was evident once again in an incident in 1999; Voganeft-248, a Russian tanker, ran aground and broke apart at the Sea of Marmara entrance of the Strait. Over 1500 tons of oil spilled into the sea, and clean-up efforts lasted several months [Birpınar et al., 2005].

In 2005, almost 55,000 vessels passed through the Strait, an increase of 16% over the previous year. Inevitably, as the number of vessels transiting the Strait increases dramatically, so will the likelihood of accidents and their adverse consequences, endangering the only city in the world that stands astride two continents, and its 12 million inhabitants. Therefore, determining martime risks and measures to mitigate these risks becomes of utmost importance.

The goal of this research is to analyze the risks involved in the transit vessel traffic in the Strait of Istanbul and provide policy suggestions to reduce safety risks. We have developed a detailed mathematical risk model to be used in the risk mitigation process to improve safety in the Strait. In the first step of the risk analysis, the transit vessel traffic system in the Strait of Istanbul is thoroughly analyzed and a simulation model is developed to mimic maritime operations and the surrounding environmental conditions as depicted in Figure 2.

Figure 2 A snapshot from the simulation model



Risk analysis of the Strait is performed by incorporating a probabilistic accident risk model into the simulation model. Probabilistic arguments utilized historical accident data, as well as subject-matter expert opinions. We have also performed a scenario analysis, in order to study the behavior of accident risks as a function of various natural, environmental and regulation lead conditions and arrive at some critical policy suggestions.

2 Literature on Maritime Risk Analysis

The risk analysis literature in maritime systems mainly focuses on probabilistic risk analysis, simulation modeling and statistical analysis of data. Below, we present a brief overview.

[Atallah and Athens, 1984] provides general guidelines for the application of risk assessment methodology to existing or proposed marine terminal operations. [Haya and Nakamura, 1995] proposes a quantitative risk evaluation procedure that systematically combines various simulation techniques including the degree of collision risk of a ship felt by the shiphandler.

[Harrald *et al*., 1998] describes the modeling of human error related accident event sequences in a risk assessment study of maritime oil transportation in Prince William Sound, Alaska. [Merrick *et al*., 2000] and [Merrick *et al*., 2002] present a simulation model of the Prince William Sound oil transportation system developed primarily for risk mitigation purposes. [Merrick *et al*., 2001] discusses the Washington State Ferries Risk Assessment through a modeling approach combining simulation, expert judgment and risk analysis. [Van Dorp *et al*., 2001] describes a study assessing the sufficiency of passenger and crew safety in the Washington state ferry system, while focusing on the estimation of the level of risk present and possible risk reduction measures. As a supplement to [Merrick *et al*., 2001], the potential consequences of collisions are modeled to determine the requirements for onboard and external emergency response procedures and equipment. [Merrick and Van Dorp, 2006] combines a Bayesian simulation of the occurrence of situations with accident potential and a Bayesian multivariate regression analysis.

Literature also includes statistical approaches to model accident probabilities and casualties. [Maio *et al*., 1991] develops a regression model to estimate the waterway casualty rate depending on the geographic conditions. [Roeleven *et al*., 1995] describes a forecasting model for the probability of accidents as function of waterway attributes and circumstances. [Kite-Powell *et al*., 1998] developed physical risk model is based on a set of risk factors, including human error and vessel characteristics. [Moller *et al*., 2005] reviews the current status of the government-industry partnerships for dealing with oil spills as the result of maritime transportation.

We have also focused on the risk analysis of the traffic in the Strait of Istanbul. [Kornhauser and Clark, 1995] used the regression model developed by [Maio *et al*., 1991] to estimate the vessel casualties resulting from additional oil tanker traffic through the Strait of Istanbul. [Otay and Özkan, 2003] developed a simulation model to estimate the probability distribution of vessel casualties using the geographical characteristics of the Strait of Istanbul. [Tan and Otay, 1998] and later [Tan and Otay, 1999] present a physics-based stochastic model to investigate casualties resulting from tanker accidents in the Strait of Istanbul. The authors demonstrate a Markov chain model to represent locations of vessels at the waterway to estimate the probability of casualty at a given location. [Or and Kahraman, 2002] investigates possible factors contributing to accidents in the Strait of Istanbul using Bayesian analysis and simulation modeling.

3 Modeling Risk

Investigations of past maritime accidents have indicated that accidents are almost always in consequence of or related to a trigerring incident. For example, there can be a mechanical failure in the vessel or the captain can make an error at a difficult spot in the Strait leading to an accident. These causal occurrences that may trigger an accident are referred to as *instigators*.

Accident trigerring incidents include human error, rudder failure, propulsion failure, communication and/or navigation equipment failure, and mechanical and/or electrical failure. Clearly, the occurrence of an instigator depends on the *situation*, which may be represented by a vector of situational attributes. Typical accidents that may occur in the Strait include collision, grounding, ramming, sinking and fire and/or explosion. Accidents may occur in chain, in such a way that an accident may cause another one. *1st tier accident* types include collision, grounding, ramming and fire and/or explosion, while the *2nd tier accident* types (that may occur following a 1st tier accident) include grounding, ramming, fire and/or explosion, and sinking. Potential consequences of the 1st and 2nd tier accidents include human casualty, property and/or infrastructure damage, environmental damage and loss of traffic effectiveness and throughput.

Defining situations is critical for risk analysis since they influence the likelihood of instigators for accidents. Here we will introduce the concept of situational attributes to be able to define all the situations that may occur during a vessel transit. We divide the situational attributes into two groups: attributes influencing accident occurrence and attributes influencing consequences. The attributes influencing accident occurrence can be classified as vessel attributes and environmental attributes as given in Figure 3. Similarly, attributes influencing consequences have two categories, vessel attributes and shore attributes, as listed in Figure 4.

Figure 3 Situational attributes influencing accident occurrence

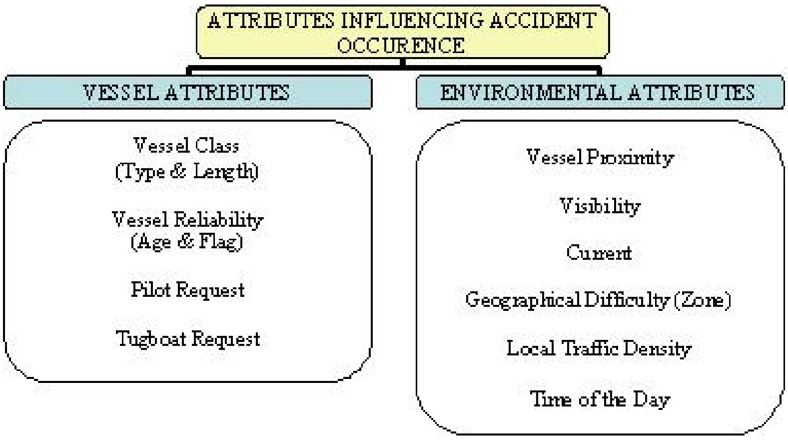
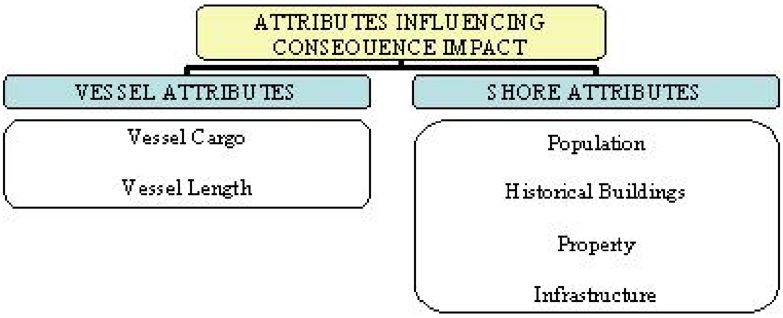


Figure 4 Situational attributes influencing the consequences



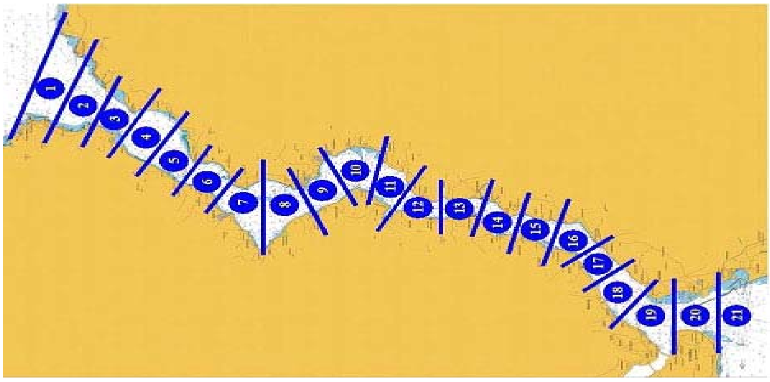
Note that in order to quantify risks, we need to answer the following questions:

- How often do the critical situations occur?
- For a particular situation, how often do instigators occur?
- If an instigator occurs, how likely is an accident?
- If an accident occurs, what would the damage to human life, property and environment be?

In this study, risks are quantified based on historical data, expert judgment elicitation and a high-fidelity simulation model of the transit vessel traffic in the Strait of Istanbul. Detailed vessel/traffic data has been obtained from the Turkish Straits Vessel Traffic Services (VTS) and meteorological data from various sources. The simulation model mimics the arrivals of transit vessels grouped in five type classes (as tankers, dangerous cargo carriers, LNG-LPG carriers, dry cargo carriers and passenger vessels), and in various length classes The model then mimics the scheduling of vessel entrances, their pilotage and transit travel (with details such as speeds and overtaking), and their exit from the Strait, all according to the Strait traffic rules and regulations, along with all the relevant local traffic, weather and current conditions. The scheduling algorithm is developed through a close cooperation with the VTS to mimic their decisions on sequencing and scheduling vessel entrances in daytime and nighttime, as well as the start time and length of the time-window regarding vessel traffic in either direction [Uluscu et al., 2009]. The model is tested through a validation process and the results have been satisfactory.

In the model, the Strait of Istanbul is divided into 21 slices (each 8 cables long, where 8 cable = 0.92 miles) for risk analysis purposes as depicted in Figure 5. The risk at a slice is calculated based on the snapshot of the traffic in that slice every time a vessel enters it.

Figure 5 Risk slices at the Strait of Istanbul



In order to calculate risk, the product of two sets of factors is sought for associated with each transit: the probability of an accident and the potential consequences of this accident, during that particular transit. Since two groups of accidents are considered, 1st and 2nd tier accidents, the expected slice risk can be calculated accordingly.

$$R = \sum_{\substack{Vessels \\ navigating}} \sum_{\substack{1st\ tier \\ accident\ types}} \sum_{\substack{2nd\ tier \\ accident\ types}} \left(\sum_{\substack{Consequence \\ types}} E\left[Consequence\ type \,|\, 1st\ tier\ accident\ type\right] \times \Pr\left(1st\ tier\ accident\ type\right) + \sum_{\substack{Consequence \\ types}} E\left[Consequence\ type \,|\, 2nd\ tier\ accident\ type\right] \times \Pr\left(2nd\ tier\ accident\ type\right) \right)$$

$\Pr\left(1st\ tier\ accident\ type\right)$ is obtained using conditional probabilities of all possible accidents given situations (e.g. visibility) and instigators (e.g. human error); conditional probabilities of instigators given situations; and finally probabilities of situations.

$\Pr\left(2nd\ tier\ accident\ type\right)$ is obtained using conditional probabilities of all possible 2nd tier accidents given 1st tier accidents and probabilities of 1st tier accident occurrences.

$E\left[Consequence\ type \,|\, Accident\ type\right]$ is obtained using the consequence impact levels, conditional probabilities of all possible consequences given accidents and situations and finally probability of situation.

In order to calculate risk, R as defined above, some of the accident probabilities (due to situations and instigators) and consequence probabilities (of accidents and situations) are obtained via elicitation of expert judgments. Other probabilities (e.g. instigator and 2nd tier accidents probabilities) are obtained from the historical data.

Experience has shown that maritime accidents can be quite different from one another in terms of factors causing them. As introduced above, various conditional probabilities of accidents are sought after in this study. Unfortunately, historical data proved insufficient for a proper statistical analysis of these probabilities. Therefore, expert opinion is deployed in their estimation. Expert opinion on accident probabilities is obtained through an elicitation process using questionnaires focusing on pairwise, uni-dimensional (one at a time) comparisons of factor settings (while keeping the remaining factors at pre-determined fixed levels).

Accident consequences (in terms of low, medium or high effects on human life, traffic efficiency, property, infrastructure and environment) are also determined through a similar elicitation process. Furthermore, we have assumed that the quantitative values of impact levels (such as low, medium, high) of a consequence of an accident at a given slice are uniformly distributed within their associated scales. Their parameters are given in Table 1 for different levels of consequence impacts. These values do not represent the actual consequence of an accident in a specific unit (e.g. dollars or number of casualties). Instead, we utilize index values representing the experts' perception of a low, medium and high consequence. As a result, the calculated risk values are only meaningful when compared to each other in a given context. Clearly, other ways of parametrization (quantification) of the qualitative consequence level descriptions is possible (actually this is expected to be a key scenario parameter in a comprehensive scenaro analysis).

Table 1 Consequence impact levels

Impact Level	Value
Low	Uniform(0-1,000)
Medium	Uniform(4,000-6,000)
High	Uniform(8,000-10,000)

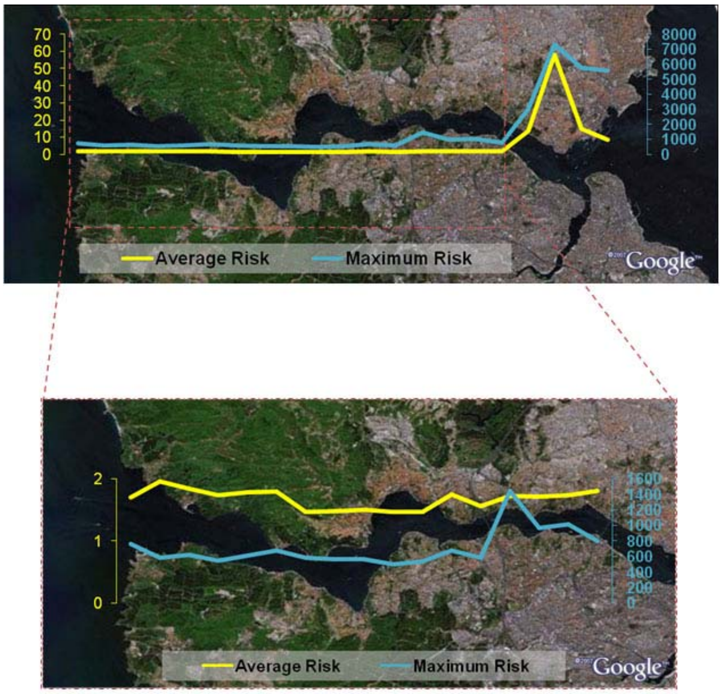
Finally, these assessments have been integrated into the simulation model such that the risks observed by each vessel at each slice are calculated considering all the natural and man-made conditions surrounding the slice (such as, vessel characteristics, pilot/tugboat deployment, proximity of other vessels, current and visibility conditions, location in the Strait etc.), as the vessels moved along the Strait.

4 Experimentation with the Model

Experimentation with the simulation/risk model described above has been accomplished through a scenario analysis. In this regard, first the parameter values reflecting the current situation in the Strait, based on year 2005-06 data (such as, vessel arrival rates, overtake and pursuit distances, vessel entrance schedules, local traffic density etc.) is compiled into a "base scenario". The risk profiles of this "base scenario" (in terms of average slice risks and average maximum risks), obtained using 25 replications (simulation runs) - each of one year length, are displayed in Figure 6. The average slice risk profile exhibits a steady behavior from the north entrance all the way down to the Bogazici Bridge, where the effects of the high local traffic activity in these highly populated and busy regions of the Strait start becoming significant. Interaction of the transit and local traffic patterns generates a large spike in the average risk in Slice 19 (this is the region corresponding to downtown Istanbul and the main harbor area) and somewhat tapers off around the south entrance. The average maximum risk profile also exhibits a similar behavior but featuring 200 to 850 fold increases from average risks levels observed at various points along the Strait. This observation indicates how risky the maritime traffic in the Strait of Istanbul can get at specific instances. That is, depending on random realizations of accident causing factors, ordinary and safe appearance of the Strait maritime activity could swiftly change into a very risky environment. Such potentially highly dangerous situations may be rare, but a rare disaster is a disaster too many. So, high risks indicated by the maximum risks should be taken seriously.

Next, a series of scenarios has been constructed and compared against the base scenario (through the the aggregate model), in order to investigate the characteristics of accident risks in the Strait under different settings and conditions. This analysis has provided us with the ability to observe and predict how changes in various policies and practices impact the risk profile of the Strait. The results and important observations accomplished are summarized below.

Figure 6 Current risk profiles of the Strait of Istanbul



- The accident risks in the Strait and the average vessel waiting times exhibit a tight and sensitive balance. For instance, a small increase in arrival rates may result in rather high waiting times at the entrances (an increase of 60% for some vessel classes). Furthermore, scheduling changes made to reduce vessel waiting times increase risks in the Strait substantially. Conversely, one has to be very careful in revising the scheduling mechanism for the purpose of risk mitigation, since the waiting times are highly sensitive to entrance rules. The benefits obtained in risks may not justify the resulting waiting times. In the future, scheduling changes may be justified, if significant reductions occur in the transit vessel traffic, perhaps due to alternative oil transport modes such as pipelines and other routes. Thus, scheduling decisions to balance out delays vs. risks should be made based on extensive experimentation with the model developed in this study.
- The model indicates that pilots are of utmost importance for safe passage, and lack of sufficient pilotage service significantly increases the risks in the Strait. Currently, vessels longer than 250 m. are mandated to take a pilot, and it is voluntary for the rest. As a result of our experimentation, we have recommended mandatory pilotage for vessels longer than 150 m. This will reduce the average risk by 7%, the average of maximum risk by 11% in Slice 19 and the observed maximum risk is 11114 observed in Slice 3 (almost 7,000-fold of its average). Had pilotage been obligatory for vessels longer than 100 m., this would reduce the average risks by 46 % and the average of maximum risks by 33 % at Slice 19.
- Even though current regulations discourage overtaking anywhere in the Strait, results indicate that overtaking a vessel is less riskier as opposed to requiring a pursuing faster vessel to slow down behind a slower vessel, where the average slice risk and the average of maximum risk are increased by 28 % and 21 % in Slice 19, respectively. In the latter case, the maximum

observed risk is 23030 (almost 13,000-fold of its average) observed in Slice 1. Therefore, in the regions where the geography of the Strait tolerates it, overtaking seems to be a safe practice (as also suggested by expert opinion).

- The most significant contributor to risk appears to be the juxtaposition of the transit vessel traffic and the local traffic. When the local traffic density in the Strait is decreased by 50% during daytime, it results an 83% decrease in the average risk and 31% decrease in the average maximum risk of Slice 19. Accordingly, for potential risk mitigation, the scheduling procedure maybe revised to enable a more effective night-time traffic at which time there is almost no local traffic. However, this issue requires further research regarding the kind of modifications that can be done to the scheduling practice to accommodate a larger volume of night-time traffic, hopefully without increasing overall vessel delays or other risks.

5 Conclusion

The nature of the global economy dictates that the tanker traffic in the Strait of Istanbul cannot be eliminated. Nonetheless, the economic aspirations and environmental awareness need not to be mutually exclusive goals in the Strait. The risks involving the transit traffic can be mitigated by operational policies and restrictions that adequately regulate the transit vessel traffic while maintaining the freedom of passage. Until then, the environment, the priceless historical monuments and the health and safety of the city's residents will be at jeopardy.

In this study, we have carried out a comprehensive analysis of safety risks of the maritime traffic in the Strait of Istanbul. We have developed an understanding of the vessel transit operations in the Strait through a serious collaboration with the key parties such as Turkish Straits Vessel Traffic Services (VTS), among others. Consequently, we have developed a detailed hybrid mathematical/simulation model using data from a large number of sources. The model is a valid representation of the maritime traffic operations at the Strait of Istanbul and the results are quite accurate and realistic. Our conclusions are in the direction of maintaining the current scheduling/sequencing procedures to let vessels enter the Strait, enforcing pilotage on a larger scale and possibly moving more vessel volume to night-time transit in order to reduce their interaction with the day-time local traffic.

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