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Simulation-Based Risk Analysis of Maritime Transit 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 gives due consideration to current traffic rules and regulations, transit vessel profiles and schedules, pilotage and 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. Unfortunately, historical accident data is by far insufficient for a proper statistical consideration of all possible settings of these factors. Therefore, subject-expert opinion is relied upon in estimating these conditional accident probabilities. Assessment of the consequences of a given accident (in terms of its effects on human life, traffic efficiency, property and environment) was also accomplished using a similar approach.

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 (the Straits of Istanbul and Canakkale), which have narrow and winding shapes that give them the semblance of a river, are one of the most strategically important waterway systems in the world. As the Black Sea's sole maritime link to the Mediterranean and the open seas beyond, they are a vital passageway not just for trade but for the projection of military and political power. Also, their hard to navigate geographical properties, meteorological conditions, dense and increasing transit/local traffic, vessel/cargo characteristics, and physical hindrances, such as cross continental bridges, energy transfer lines, make the Straits' traffic conditions quite complex and risky. Moreover, this narrow passage runs through the heart of Istanbul, home to over 12 million people and some of the world's most celebrated cultural and historical heritage.

Geographically, the Strait of Istanbul is one of the narrowest waterways in the world. It has length of 31 kilometers with an average depth of 45 meters (Ozturk, 1995). Its average width is 1.5 km, where this width decreases to 700 meters at its narrowest point (Tan & Otay, 1999). Additionally, frequent adverse meteorological conditions, such as dense fogs and high currents and winds, contribute to the complexity of navigation in the Strait.

There are also some non-natural factors making navigation through the Strait of Istanbul hazardous. One of them is the dense local traffic, such as intracity passenger boats, fast ferries, fishing boats, pleasure boats, tugboats etc. (VTS User Guide, 2004). Another important non-natural factor that negatively effects navigation in the Strait is the frequency and cargo characteristics of transit vessels. Over 56,600 vessels (10,050 being dangerous material carriers) traveled through the Strait of Istanbul in 2007.

In order to control and mitigate maritime accident risks and improve the safety of navigation in the described dire environment, The Bureau of Turkish Strait's Maritime Traffic Services (BMTS) has set up a sophisticated Vessel Traffic Control & Monitoring System (VTS), (covering not only the Strait, but also 20 miles into the Black Sea and the Sea of Marmara) and has established and effected a set of stringent Maritime Traffic Rules and Regulations (R&R). The vessels arriving at the northern and southern entrances of the Strait of Istanbul enter and then navigate through the Strait according to the directions of the BMTS, which are based on the VTS inputs and the R&R (VTS User Guide, 2004).

Figure 1. The Strait of Istanbul

The objective of this study is to analyze the risks involved in the transit vessel traffic in the Strait of Istanbul. In order to achieve this, a detailed mathematical risk analysis model is developed to be used in a risk mitigation process (Uluscu et al., 2008). Firstly, in order to study and better understand the system, a functional simulation model of the transit vessel traffic in the Strait of Istanbul is built. In this simulation, which is based on the mentioned R&R, in addition to the geographical/meteorological conditions, transit and local vessel traffic in the Strait, the current vessel scheduling practices are also modeled using a specially designed scheduling algorithm. This scheduling algorithm, which is developed through discussions with the BMTS authorities, primarily mimics their decisions on sequencing vessel entrances, as well as northbound and southbound traffic flow time windows (Uluscu et al., 2009). Finally, by integrating, expert opinion and historic data based risk assessments into the developed simulation model, the risks generated by each vessel, are calculated in regard to the natural and man-made conditions surrounding it (such as, vessel characteristics, pilot/tugboat deployment, proximity of other vessels, current & visibility conditions, location in the Strait etc.), as the vessel moves along the Strait. Preliminary results obtained in the application of this procedure are presented and discussed in later sections.

2 MODELING RISK

The primary objective of this study is to develop a realistic model to assess and investigate maritime risk imposed by the transit traffic in the Istanbul Strait; furthermore, it is expected that such a model and an accompanying scenario analysis will suggest and support strategies and operational policies that will mitigate the risk of maritime accidents that will endanger the environment, the inhabitants of Istanbul and impact the economy, while maintaining an acceptable level of vessel throughput.

Regarding the modeling of risk, first events that may trigger an accident are identified and defined as instigators (for example, there can be a mechanical failure in the vessel or the captain can make a judgmental error, during the transit of the vessel through the Strait of Istanbul). Through the examination of the historical accident data and discussions with local maritime experts, the occurrences of the following incidents have been identified as possible instigators of maritime accidents in the Strait: human error, rudder failure, propulsion failure, communication and/or navigation equipment failure, and other 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. Given the occurrence of an instigator, typical accidents that may occur in the Strait have been considered and classified as, collision, grounding, ramming, sinking and fire and/or explosion. It is also possible to have accidents may occurring in chain, so that a prior (1st tier) accident may cause later (2nd tier) one. 1st tier accident types include collision, grounding, ramming and fire and/or explosion, while the 2nd tier accident types 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. This framework is presented in Figure 2. Defining situations (factors and their states) that affect the likelihood and/or impact level of instigators and accidents is critical for the intended risk analysis. Such factors as called Situational Attributes, and are divided into two groups: attributes influencing accident occurrence (vessel class, vessel reliability, pilot request, tugboat request, visibility, current, local traffic density, vessel proximity, zone and time of the day) and attributes influencing consequences (vessel cargo, length, zone). These two groups of situational attributes (are displayed in Figure 3 and 4.

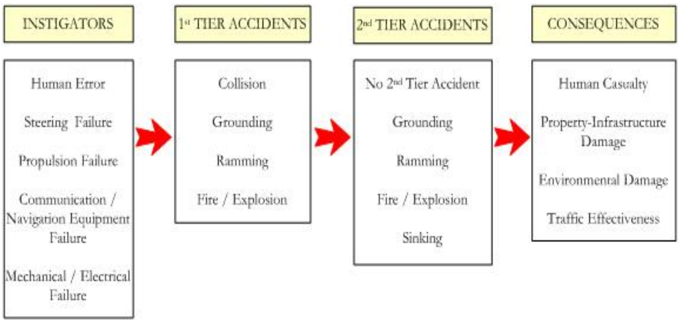

Figure 2. The framework of the risk model

Given the above described framework, the following questions need to be answered in order to quantify risks:

- 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, environment and infrastructure be?

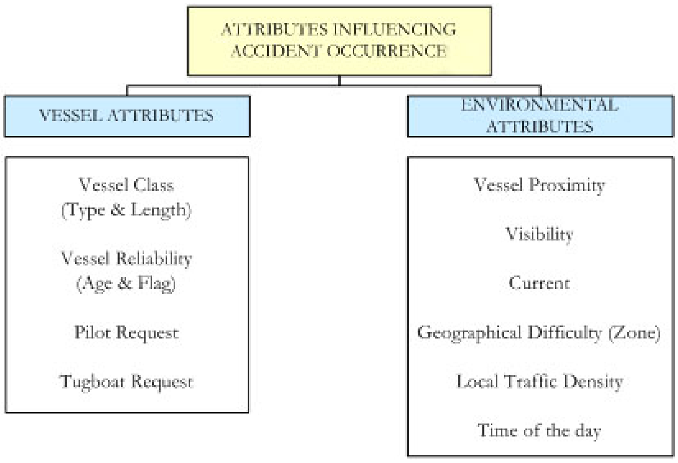

Figure 3. Situational attributes influencing accident occurrence

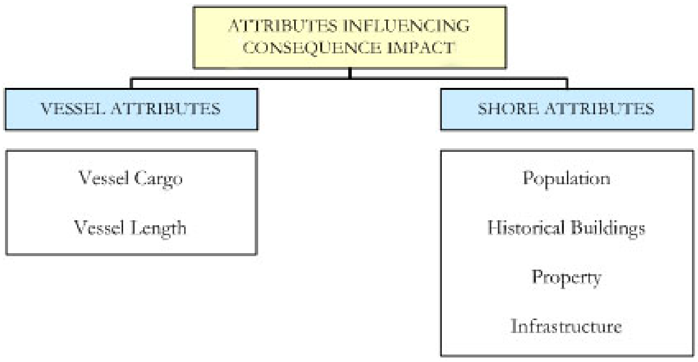

Figure 4. Situational attributes influencing the consequences

In this study, answers are provided to these questions (and risk quantification accomplished) based on historical data, expert judgment elicitation and simulation model generated output regarding the state of the situational attributes. The 21 slice division of the Istanbul Strait, depicted in Figure 5 (each slice being 8 cables long) assumed in the simulation model, is also pursued for risk analysis purposes. The risk at a slice is calculated based on the snapshot of the traffic in that slice every time a vessel enters it.

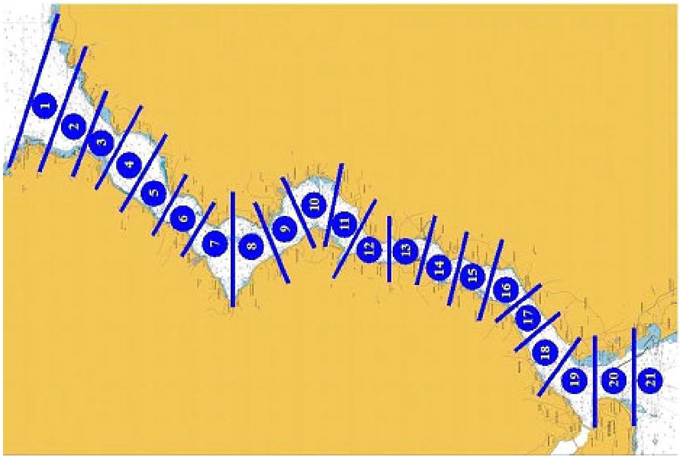

Figure 5. Risk slices at the Strait of Istanbul

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 (1^{st} and 2^{nd} tier accidents), the expected slice risk can be calculated accordingly.

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

$\Pr\left(1st\ tier\ accident\ type\right)$ 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 2^{nd} tier accidents given 1st tier accidents and probabilities of 1^{st} tier accident occurrences.

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

To be able to calculate the expected risk, *R,* as shown above, most of the accident and consequence probabilities (conditioned on the occurrence of instigators and/or state of situational attributes) are obtained via elicitation of expert judgments; other probabilities (e.g. instigator and 2nd tier accidents probabilities) are obtained from the historical data. The specific states of the many situational attributes are obtained from the simulation model (as the vessels generated in the model move through the Strait, in the environment also generated by the model)

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 has been insufficient for a proper statistical analysis of these probabilities. Therefore, expert opinion has been relied upon 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 (situational attribute) settings (while keeping the remaining factors at pre-determined fixed levels).

Conditional probabilities of 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. On the other hand, quantification of these qualitatively defined impact levels is accomplished through parameterization. One such set of parameters assumed (for different levels of consequence impacts) is presented in Table 1. These values do not represent the actual consequence of an accident in specific units (e.g. dollars or number of casualties). Instead, index values representing the experts' perceptions of low, medium and high consequences are utilized. As a result, the calculated risk values are meaningful when compared to each other in a given context.

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 are integrated into the simulation model such that the risks observed by each vessel, at each slice are calculated and compiled considering all the natural and man-made conditions surrounding the slice and the vessel (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.

3 OBSERVATIONS

Experimentation with the aggregate 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 2005-2006 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 Strait region corresponding to downtown Istanbul and including 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 remarkable 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. For example, a rare realization observed in Slice 1 (corresponding to risk value 12210) involved an excessive level of fog during nighttime and two D-class vessels that just entered the slice before the Strait is closed. Another rare realization, observed in Slice 19 (corresponding to risk value 10710), involved an A-vessel that was about to leave the Strait just after the night schedule started, a D-vessel and an E-vessel along with 10 local vessels. 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 aggregate model), in order to investigate the characteristics of accident risks in the Strait under different settings and conditions. In Scenarios 1 and 2, arrival rate of hazardous cargo vessels are increased and decreased. In Scenarios 3-9, vessels are scheduled with lesser and greater pursuit distances. In Scenario 10, pilot captain service is turned off. Scenario 11 represents the case where overtaking is not allowed within the Strait. Finally, local traffic density in the Strait is decreased by 50% in Scenario 12. An average maximum slice risk profile is given in Figure 7.

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.

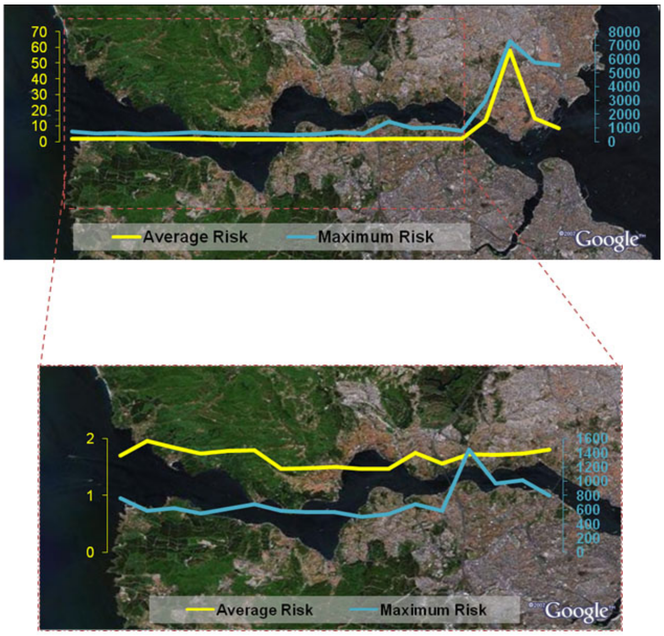

Figure 6. Current risk profiles of the Strait of Istanbul

3.1 *Observation 1*

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.

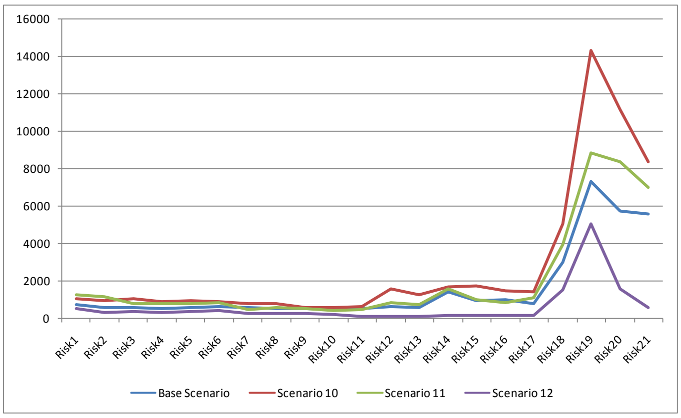

Figure 7. Maximum Slice Risk in Scenarios 10, 11, and 12 compared to the Base Scenario

3.2 *Observation 2*

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.

3.3 *Observation 3*

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).

3.4 *Observation 4*

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.

4 CONCLUSION

The nature of the global economy and international politics dictates that the maritime transit traffic in the Strait of Istanbul cannot be greatly reduced nor eliminated. Nonetheless, the economic/political realities and environmental awareness and risk management need not to be mutually exclusive goals in the Strait. The risks regarding the transit traffic can be mitigated by operational policies and rules that adequately regulate and guide the transit traffic, while maintaining the freedom of passage. Until then, the environment, the priceless historical/cultural heritage and the health and safety of the city's residents will be at jeopardy.

In this paper, a comprehensive analysis of safety risks of the maritime transit traffic in the Strait of Istanbul is discussed. This analysis is carried out through the development and deployment of a detailed hybrid mathematical/simulation model. This model, which is based on extensive objective and subjective data from a large number of sources, provides a realistic and valid representation of the maritime traffic operations and their impacts at the Strait of Istanbul with many interesting results.

Our primary conclusions are in the direction of maintaining the current scheduling/sequencing procedures to let transit vessels enter the Strait, while enforcing pilotage service on a larger scale and seeking more efficient and heavier deployment of night-time conditions, where the local traffic activity is almost negligible.

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