Transactions on Operational Research
Vol. 17, November 2006, pp. 20–37

Yöneylem Araştırması Dergisi
Cilt 17, Kasım 2006, s. 20–37

Simulation of Maritime Transit Traffic in the İstanbul Channel

Birnur Özbaş[1], **İlhan Or**[2]

[1] Boğaziçi University, Industrial Engineering Department, Bebek 34342, İstanbul, Turkey
e-mail: birnur@ozbas.com.tr
[2] Boğaziçi University, Industrial Engineering Department, Bebek 34342, İstanbul, Turkey

Recieved: 30 September 2005, Accepted: 17 July 2006

Abstract. This study involves a functional simulation model for the maritime transit traffic in the İstanbul Channel that investigates the Channel Traffic Rules and Regulations, vessel types, cargo characteristics, meteorological and geographical conditions, pilotage and tugboat services. The simulation model mainly focuses on the transit traffic in the Channel. It assumes two primary transit lanes and one additional lane for overtaking. The entities of the model, which are comprised of five types of vessel, and their attributes are generated randomly according to the historical data. The arrived vessels check if the Channel is available and safe for the passage against the Rules and Regulations. This study provides a platform to analyze the effects of factors such as Maritime Traffic Rules, number of tugboats and pilots, vessel type, traffic density and meteorological conditions on the maritime traffic in the Channels. Results obtained and reported in the study clearly indicate some interesting relationships among these factors. As the effect of six factors on 8 responses are examined, the most significant factor is determined as number of pilots and tugboats in the service, while the second effective factor is the arrival rate of vessels.

Key words: Simulation, İstanbul Channel, maritime transportation

1 Introduction

The sea transportation is one of the ways of transportation. As in other types of transportations, shipping has its own regulations and exceptions because waterways create different risks for the vessels. The level of this risk is at lower levels while ships travel in the deep sea. On the other hand, when a ship is near land or in a narrow waterway, the level of risk becomes considerable.

The İstanbul Channel is one of these risky areas due to some of its characteristics. Geographically, the İstanbul Channel is one of the narrowest waterway in the world. The İstanbul Channel has length of 31 kilometers with average depth of 45 meters (Öztürk, 1995). Its average width is

Corresponding author: Birnur Özbaş

1.5 km, where this width decreases to 700 meters at its narrowest point (Anadoluhisarı - Rumelihisarı) (Tan and Otay, 1999). Another property of the İstanbul Channel that makes it more risky is the meteorological conditions in this region. Current, fog, wind and rain are the major factors that are affecting navigation in the Channel, either directly or through their effects on visibility and currents.

There are also some non-natural factors making navigation through the İstanbul Channel hazardous. One of them is the local traffic such as ferries, intra-city passenger boats, fast ferries, fishing boats, agent boats, tugboats etc (VTS, 2005). Another important non-natural factor that affects the risk level in the Channel is the vessel frequency and cargo characteristics of transit passages. Over 50,000 vessels (4300 oil takers) traveled through the İstanbul Channel even way back in 1997 (Tan and Otay, 1999). As the traffic density in the Channel is so high, casualties become almost inevitable. On the other hand, a vessel's technical properties (such as age, type, length, draught, maintenance, and safety systems) and cargo affect its speed, safety, and reliability. The pilotage and tugboat services undertaken by a transit vessel is another subject that should be considered. It is strongly recommended that all direct passing vessels take a local pilot captain and even be accompanied by a tugboat to ensure the safety of life, property and the environment as well as the safe navigation within the different and risky structure of the Channels.

The natural or non-natural factors affecting the safety of transportation in the Turkish Channels, as well as the accidents realized in the past, have necessitated some stringent rules and procedures for transit vessels (called the Turkish Straits' Maritime Traffic Regulations) and a sophisticated Vessel Traffic Control and Monitoring System. As a result, the Vessel Traffic System (VTS) came into view. The vessels arriving at the north or south entrance of the İstanbul Channel enter the Channel according to the directions of the Channel Traffic Control Authority, which uses strict and well defined regulations, rules and all other conditions that are received by VTS radars, sensors and stations. The main objective of the regulations and the VTS is to reduce the maritime transportation risks in the Channel.

The objective of this study is to create a functional simulation model (based on the mentioned Rules and Regulations) for the transit vessel traffic in the İstanbul Channel, in order to provide a powerful and practical environment to evaluate transit traffic related alternatives relying on the rules, procedures and also on experiences and vessel transit statistics. Moreover, this study provides a platform to analyze the effects of factors such as transit rules, number of tugboats and pilots available, transit vessel type, priority, characteristics and density and meteorological conditions, on the maritime traffic in the İstanbul Channel.

The model includes:

- Vessel arrivals at the north and south entrance of the İstanbul Channel,
- Vessel types, characteristics and cargo carried,
- The Channel Maritime Traffic Rules and Regulations,
- The pilotage and tugboat conditions and availability,
- Meteorological conditions (visibility).

2 Literature Survey

For several years, many studies on the Istanbul Channel Traffic and on the maritime traffic in other narrow waterways around the world are examined. Also some risk management and analysis studies about the İstanbul Channel are examined in order to have an insight on the topic since this study is planned to be used as a tool in further risk management studies. As there are many studies on these subjects, a review of the most recent and most important studies are sufficient to understand the main frame of the topic.

Franzese et al. (2004) present the methodologies and preliminary results of their study to develop a simulation model of the Panama Canal, one of the most famous waterway and locks system of the world. The developed simulation model is used as a planning tool (Franzese et al., 2004). Furthermore in year 2003, Köse and his colleagues simulate the maritime traffic in the İstanbul Channel. In this research, the simulation of the İstanbul Channel is done under unique traffic conditions (current and visibility conditions, suspending due to large vessel passages and traffic separation scheme) (Köse et al., 2003).

Or and Karaman, and Or and Tayanç also investigate accident risks in İstanbul Channel. In the first study which involves a simulation study of the accident risk in the İstanbul Channel, Bayesian Analysis is used to investigate possible factors contributing to accidents throughout the Channel (Or and Kahraman, 2001). In the second risk analysis study, which involves an expert judgment based study of accident risk in the Istanbul Channel, the Analytic Hierarchy Process is used to investigate physical, environmental and technical factors which affect the navigation of vessels throughout the Channel this leads to the examination of possible factors contributing to accident risk (Or and Tayanç, 2003).

Otay and Özkan, and Yazıcı have two different studies on navigation of vessels throughout the İstanbul Channel. One of these studies is a mathematical model, which is developed to simulate the random transit maritime traffic through the İstanbul Channel. Based on the geographical characteristics of the Channel and random distributions of surface currents, arrival of transit vessels, vessel sizes and pilotage errors, the model computes probability distributions of northbound and southbound vessel positions within the Channel. The outputs are then analyzed to evaluate risk maps of collision, ramming and grounding events along the Channel for different vessel sizes (Otay and Özkan, 2003). In the second study, which involves dynamic determination of the safest navigation route for transit vessels in the İstanbul Channel, a real time traffic control tool is developed to propose a safe route to navigating vessels in the Channel. The model uses Channel geometry, bathymetry, counter traffic and the currents as the disturbances (Yazıcı, 2004).

In a different study, Otay and Tan investigate vessel casualties resulting from tanker traffic through narrow waterways. They present a physics-based stochastic model for their purpose. Risk measures such as the casuality probabilities at a given location and the expected number of casualties for a given number of vessels arriving per unit time are obtain from this study (Tan and Otay, 1999).

The previous studies on the İstanbul Channel did not make use of all the Rules and Regulations that are used by the VTS, but a subset of these rules. Moreover, these selected rules have been used to reach specific conclusions about navigational or safety properties of the Channel, not to build a complete model of the transit traffic. In order to have a tool that can be used to experiment on several factors affecting the transit traffic, a simulation-based model is necessary. However, the previous studies were usually mathematical models and analytical solutions. The few simulation models on the İstanbul Channel focused on suspending rather than overall Rules and Regulations. This model, unlike the previous ones, is a complete application of rules that can be used as a real-time decision support tool by the Traffic Control Authority and as a scenario analysis instrument that analyzes effects of different factors.

3 Objectives of the Model

As mentioned above, the objective of this study can be listed as:

– Building a simulation model, which realistically reflects the current conditions influencing the behavior of transit vessels in the İstanbul Channel, and thereby correctly mimics the flow of transit traffic itself,
– Incorporating the Channel's Traffic Control Authority's decision strategy by using same criteria to order, regulate and authorize transit vessels' passing process through the İstanbul Channel,
– Obtaining a platform for analyzing all rules, procedures, geographical and meteorological conditions affecting the status of Maritime Traffic in the İstanbul Channel,
– Obtaining a tool to support real time decision making at the Traffic Control Authority,
– Predicting the effects of increasing transit traffic demand (collectively or by vessel type and characteristics), adverse meteorological conditions, changes in the level of services provided (such as tugboats and pilot captains), and vessel class priorities by scenario analysis,
– Investigating the effects of various interpretations and changes in the application of Traffic Rules and Regulations,
– By experimenting with different vessel prioritization schemes, reducing the waiting times of vessels (or certain types of vessels), dangerous pile ups (of waiting vessels) and undesirable transit vessel densities (in certain parts of the Channel),
– Determining pilot captains' and tugboats' availability target levels and expected utilizations at those levels for a given level of transit traffic demand in order to reduce delays for those vessels that need them.

4 Simulation Model of the İstanbul Channel

The simulation software package Arena 7.0 is used for the implementation of the simulation model of Maritime Transit Traffic in the İstanbul Channel. The rules, procedures, regulations, vessel characteristics, cargo types, pilotage areas, tugboat and pilot properties, meteorological conditions are modeled by the basic process modules, elements and blocks of Arena 7.0 (Rockwell Software, 2004). At this stage, an accident free approach is used during the modeling. Next the verification and validation of the model are completed and the outputs of the model are arranged according to the statistical data requirements. The model takes the transit traffic demand data (of a given period) from input files and processes them according to the current Channel Traffic Rules and Regulations, assumed meteorological conditions, accepted service (pilots and tugboats) availabilities and vessel priorities. Vessel types, characteristics and cargo are an integral part of the transit traffic demand data set.

4.1 Inputs of the Model

The input data of the system can be listed as: transit vessels' interarrival times, types, lengths, draughts, speeds, pilot and tugboat demands, entrance directions and Channel visibility. The simulation model is designed and developed such that all input factors mentioned can be randomly generated based on probability distributions obtained from historical data. This historical data is obtained from three resources; Sea Traffic Regulation Administration's annual information and statistics report on the transit traffic in the Turkish Channels (STRA), vessel based transit traffic data for the year 2005 (obtained from VTS) and expert interviews. Information about the inputs of the model and how they are estimated are given in Table 1.

The histogram of existing entrance times of the vessels in year 2005 showed that there is a significant difference between the interarrival times of the vessels arriving at daytime and night.

Table 1. Input data information

Input Factor	*Information*	*Distribution*
Visibility	2005 real data	Empirical
Interarrival Time	2005 real data	Weibull for night and Lognormal for daytime
Vessel Type	2005 real data	Empirical
Vessel Length	2005 real data	Empirical
Vessel Draughts	1999 STRA data	Empirical
Vessel Speed	2005 real data	Uniform
Entrance Direction	1999 STRA data and personal interviews	Empirical
Pilot and Tugboat Demand	1999 STRA data and personal interviews	Empirical
Pilot and Tugboat Availability	Personal interviews	Deterministic

Table 2. Ship type probability distribution

Ship Type	***Probability***
1 (passenger vessels)	0.03
2 (LNG-LPG carrying vessels)	0.005
3 (hazardous material carrying vessels)	0.02
4 (tankers)	0.165
5 (general cargo carrying vessels)	0.78

Therefore the day is divided into two periods; daytime is assumed between 04:00 a.m. and 17:00 p.m. and nighttime for the rest. The interarrival times of the nighttime arrived vessels have been analyzed in Input Analyzer software package of Rockwell and the results showed that the best fitting distribution is Weibull with parameters 655.15 and 0.663 for the given data set. Similarly, the Input Analyzer have suggested the Lognormal distribution with parameters 493.4 and 1334.5 for the probabilistic estimation of daytime vessel interarrivals. Additionally, Sailing Plan 2 (SP-2) reporting times of actual arrivals can also be deployed for real-time applications.

Vessel types are listed in five different classes, as the Channel Traffic Rules and Regulations defines rules for five different types of vessels. These are, passenger vessels, LNG-LPG carrying vessels, hazardous material (HazMat) carrying vessels, tankers and general cargo carrying vessels. Type of an arriving vessel is determined by an empirical distribution based on the real data of year 2005. The assumed probability distribution of the arriving vessels is shown in Table 2.

Another aspect considered in the model is the speed of the vessels. Historic data has indicated that vessel speed not only depends on vessel length, but also on transit direction (the strong north to south surface current of the Channel increasing transit speed of southbound vessels and decreasing those of northbound vessels). Thus, it is assumed that the speed of the northbound vessels is uniformly distributed between 6.75-12 knots and those of southbound vessels is uniformly distributed between 8.75-13 related with their lengths.

Another vessel characteristic is the draught. Draught of a vessel is generally related with its length. In the model, the draught of a vessel is randomly determined depending on the vessel length (as greater than 15 meters for vessels longer than 250 meters and less than and equal to 15 meters for vessels smaller than 250 meters (STRA, 1999)).

Actually, in the developed model, two options have been developed for the data inputing. One of them is using the random number generation features of the Arena software. The input data, which are randomly generated from assumed distributions and historical data, are assigned to the attributes. That is, random variates for the properties of the vessels are generated in Arena's blocks internally and these values are used without external intervention. This structure allows making more than one replication of the developed simulation model.

The other inputting option is reading the required data from text files and then assigning them to attributes. Five different input files are used in this structure. The reason for using such input files is to reflect the dynamic environment of the real time vessel arrivals to the simulation model. This way, if the simulation model is to be used as a decision support tool for the Traffic Control Authority, it will be possible to enter in real time the newcomers' information to the system by using these five input files. As the attributes of the vessels are reported before they arrive at the Channel, by Sailing Plan 1 (SP-1) and Sailing Plan 2 (SP-2) reporting systems, the user should have ample time to enter the information. In addition, visibility conditions, which is a natural event and hard to estimate, can be updated by the user easily, as the fog occurs in real time. In running the scenarios, this SP-1 / SP-2 based real time inputting structure, which reads input data from external files, is used.

The effects of randomness on the main results have also been examined in this study. For this purpose, two alternatives have been deployed for input generation: random generation of the input data based on probability distributions and using average values instead of random variates. Then, the results of ten replications for the random base model are collected and a 99 per cent confidence interval is calculated. It is then tested whether the results of the one replicate average base scenario is with in the calculated confidence interval of the ten replicate random base scenario. The results show that most of the 20 output responses are not in between the 99 per cent confidence interval and thus it is regarded that randomness has an important effect on the input data generation and should be considered in the scenario analysis.

4.2 Model Logic

During the development of the model, three classes of control parameters (which are, external parameters, internal parameters and Traffic Rules and Regulations) are used in order to clarify the logic of the model and to simplify the scenario analysis. External parameters can be summarized as meteorological conditions, seasons, extreme situations, transit vessel arrival rate, vessel profile and transit vessel's speed which can not be controlled by the system administrator in real life. Number of pilot captains and tugboats, transit vessel priorities and overtaking rules are the internal parameters of the model which can be controlled and changed by the system administrator. The third class is the Traffic Rules and Regulations (the Turkish Straits' Maritime Traffic Regulations), which are regarded as unchangeable.

The Channel Entrance: The simulation model developed assumes three sea lanes for transit vessels along the İstanbul Channel (one main northbound lane, one main southbound lane and an additional lane for overtaking, wherever it is allowed). The vessels arrive at the north and south entrances of the Channel according to probability distributions obtained from historical data (which is randomly generated based on historical data or read from the input file). Then the vessel type is assigned in accordance with the Ship Type attribute. The arrived vessels enter the Channel (to the northbound or the southbound lane depending on destination) upon gaining permission from the Channel Traffic Authority, whose decisions are guided by the Channel Traffic Rules and Regulations. Actually, the arrived vessel directly added to the queues named as NaturalQ_N or NaturalQ_S, according to their entrance directions. At that point the vessel is assigned two attributes; the Threshold and the Ready Time. The Ready Time is the moment that vessel is ready (for entrance to the Channel) and has to wait only for the entrance conditions to become appropriate. It is the attribute of the vessel which is used to determine its place (ordering) in the waiting queue. On the other hand, the Threshold is the attribute that determines the vessel's priority, in the sense that the Traffic Control Authority puts a "barrier" to the opposite Channel entrance, once a vessel has waited an amount of time defined by its Threshold value. Without such a "barrier", it is possible to have a series of vessels, whose presence hinder the entrance of the waiting vessel, in transit in the Channel almost continuously; thus bringing up the possibility of a vessel waiting indefinitely for the Regulations' appropriate conditions to arise. Such a barrier stops the entrance to the Channel from the opposite side, of any vessel whose presence in the Channel would hindering the entrance of the vessel waiting for the appropriate conditions. Accordingly, a vessel with a lower Threshold value would in effect be having a higher priority, since a "barrier" in favor of that vessel would be placed earlier thus reducing its average waiting time. Note that, it is still possible for a vessel to enter the Channel without putting up a barrier, if there are no vessels, whose presence hinders her entrance, in transit in the Channel. The Traffic Authority postpones the barrier rights of daytime transit vessels (i.e. those vessels which are, by regulations, allowed to make a transit only in daytime) between 4 p.m. - 7 a.m. in order not to unnecessarily hinder other vessels which can pass by night as well. These vessels are held in the wait block of Arena 7.0. The wait block holds an entity in the preceding queue block until a signal code (that given when the date changes) is received. When the signal code is received, the wait block releases entities from the preceding queue block.

Visibility: Regulations obligate that when visibility in an area within the Istanbul Channel drops to 1 mile or less, vessel traffic shall be permitted in one direction only, and when visibility drops to less then 0.5 mile, vessel traffic shall be suspended in both directions (Official Gazette, 1998). Accordingly, the vessels in the NaturalQ_N or NaturalQ_S queues check if traffic is suspended due to fog through their route. Daytime transit vessels in the NaturalQ_N or NaturalQ_S also check the date (daylight or night hours). If the requirements are not met, the vessels wait in the queues until the signal code of visibility level or date changes is received. When the visibility and daylight requirements are met, the vessels in the NaturalQ_N or NaturalQ_S queues enter to the main queue in the model named as Common Queue.

Rules and Regulations: All vessels wait in the Common Queue and check if the Channel is available and safe for the passage. Entrance to the Channel is first checked against various Rules and Regulations such as; The HazMat, LNG-LPG carrying vessels and tankers with length between 100 and 150 meters and the general cargo carrying vessels longer than 150 meters should not come across with any HazMat or LNG-LPG carrying vessel or any other type of vessel longer than 150 meters, in the Kanlıca - Vaniköy region. There are around 20 such specific rules and regulations, all of which can be found at website of Straits and Ports Maritime Pilots' Association (TBLKKD, 2005). The ranking order of this queue is according to the least value of Ready time attribute. In other words, starting with the vessel having the least ready time attribute, each vessel in the Common Queue is checked for the satisfaction of Channel Traffic Rules with respect to the existing traffic in the Channel. When there are no restrictions due to the rules, other factors such as pilot captain, service boat (used to disembark or board pilots), tugboat needs, visibility and daylight passing conditions are checked with respect to vessels type, length and draught needs and requirements. If all factors are suitable and available the vessel enters the Channel. This process is sequentially followed for all vessels in the Common Queue.

The Channel and Overtaking: In the Channel, a vessel passes through eight different zones. Each zone is divided into a sequence of "substations" which are set at a distance of 8 cables ($\approx$1.0904 miles $\approx$1.7552 km.) from one another. This is to satisfy the regulation that vessels in transit in the Channel shall maintain at least 8 cables distance between each other (Official Gazette, 1998). This distance may be increased by the Traffic Control Center depending on the type of vessel in question. Additionally the regulations state that any vessel intending to overtake another vessel that is proceeding at lower speed within the Channel, shall inform the

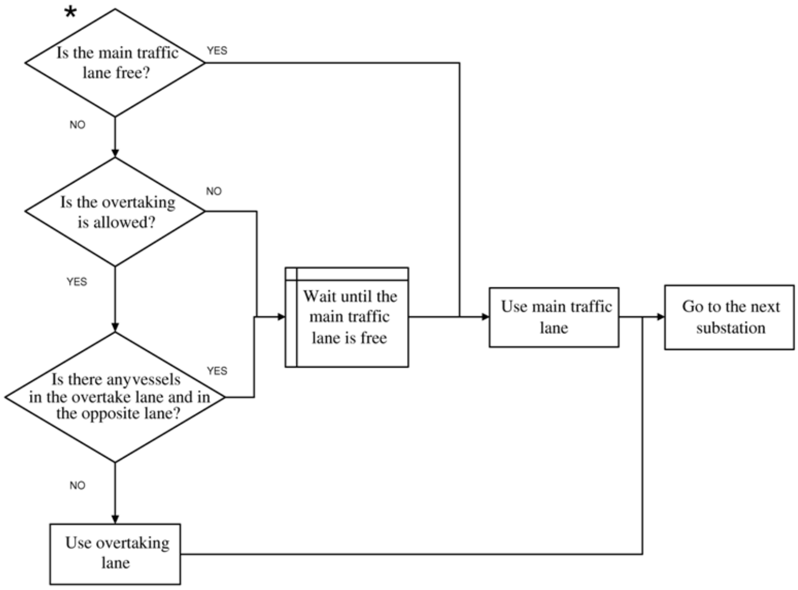

Figure 1. Overtaking logic

Traffic Control Authority, to obtain information regarding the density of traffic and indicate her intention to the vessel she plans to overtake (Official Gazette, 1998). Accordingly, in the model a vessel uses the third traffic lane during overtaking. When a vessel decides to overtake another vessel, there should be no vessels in the overtake lane, as well as in the opposite lane. During the overtaking process, the faster vessel moves through the substations in the "overtake" lane until it passes the slower moving vessel (at which time it returns to the original lane). If further substations of the overtake lane are occupied (by a vessel moving in the opposite direction or same direction) or unavailable (wherever it is not allowed), the faster vessel cannot successfully complete the overtake and moves to the substations behind the slower vessel. This control provides that at most two vessels exist side by side in an eight-cable-long substation. Additionally, since the regulations do not allow overtaking between Vaniköy and Kanlıca points (i.e. the narrowest section of the Channel), in the model the third traffic lane is removed at this section. The flow diagram of overtaking logic is given in Figure 1.

Pilotage and Tugboat Services: The pilot captain and tugboat needs of the vessels about to enter the Channel are also taken into consideration. The pilot boarding and disembarking area is around the line connecting the Hamsi Limanı and Fil Burnu Lights at the Black Sea entrance and around the Fenerbahçe Light tower at the Marmara Sea entrance (Official Gazette, 1998). In the model, if a vessel prefers (or is required by regulations) to use any of these services, it seizes them at the mentioned disembarking and boarding areas. When a pilot is seized, a service boat is also seized since service boats are used to disembark or board pilots. When two vessels demand a service boat in the same time interval, model gives priority to the disembarking vessel. Additionally, two control mechanisms added to the model for increasing the utilizations of pilots and tugboats. In any entrance, while the pilot or tugboat is released, if the number of idle pilots or tugboats is higher than or equal to defined limits, the excess pilot or tugboat is transferred to the opposite side in 30 minutes (by taxi) and 90 minutes (from the sea) respectively. Also, when

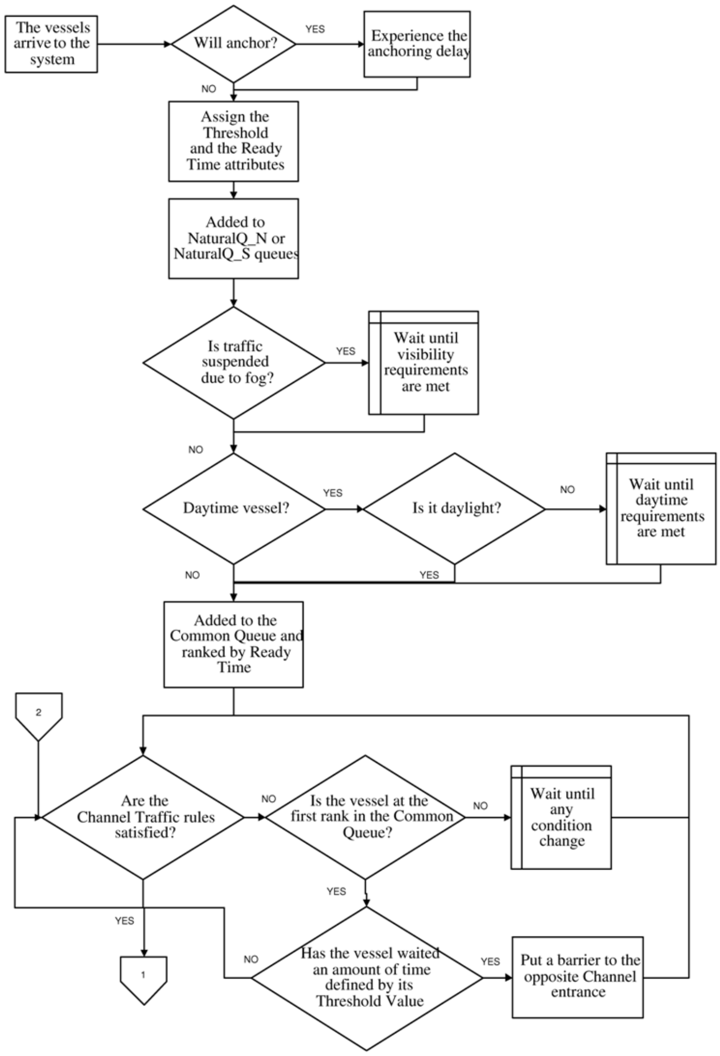

Figure 2. Model logic

a pilot or tugboat is seized, number of remaining resources is checked. If the value is zero and the other side has more than two idle of that resource, they are sent to the side in need of. During the transfer of excess pilot and tugboat, number of transferring resources is also checked by a control mechanism in order to avoid simultaneous transfers. When a vessel completes its transit of the Channel, it releases the pilot or tugboat at the disembarking area. When the seized pilot or tugboat is released, it is altered to be an available resource at the release entrance. When the vessel completes its Channel transit and all related operations, it is disposed from the model.

The flow diagram of model logic is given in Figure 2 and 3.

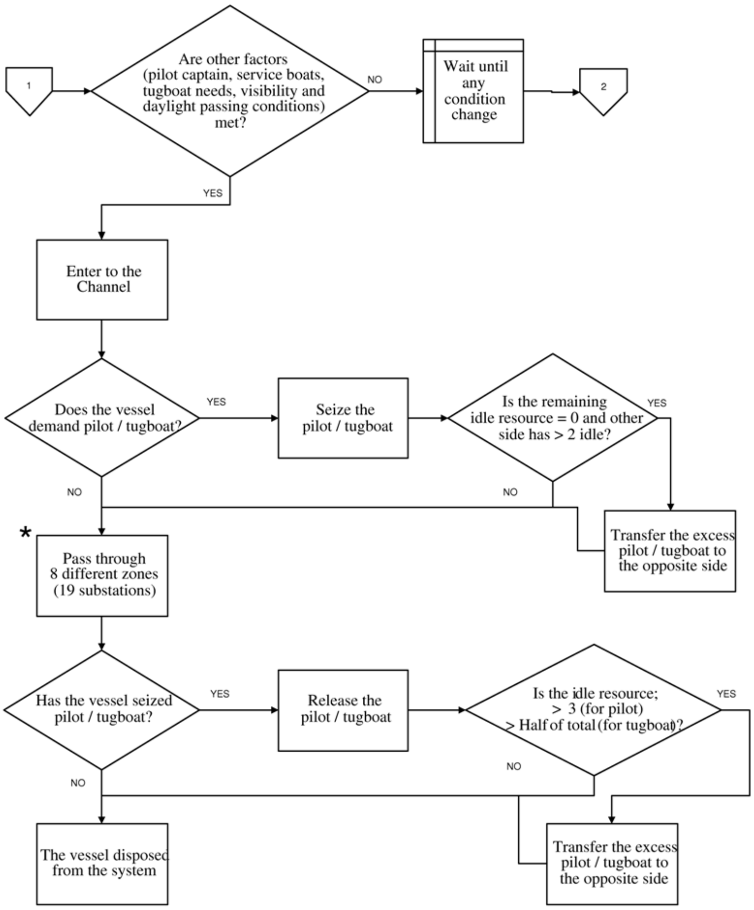

Figure 3. Model logic cont'd

4.3 Verification and Validation

After the implementation of the simulation model of the maritime transit traffic in the İstanbul Channel by modeling the rules, procedures, regulations, vessel characteristics, cargo types, the traffic flow process, the tugboat and pilot deployment processes and meteorological conditions, by aid of the above described assumptions and through exercising the basic process modules, elements and blocks of Arena 7.0, next the verification and validation of the model are accomplished.

In order to verify the simulation model, the modeling process is done in stages where each additional stage is individually debugged. Next additional subprograms and levels of detail are added and debugged successively until a model is developed that satisfactorily represents the system under study. One of the most powerful techniques that can be used to debug a discrete-event simulation program is trace. In a trace, the state of the simulated system, i.e., the contents of the event list, the state variables, certain statistical counters, etc., are displayed just after each event occurs and compared with hand calculations to see if the program is operating as intended (Law and Kelton, 2000). In the simulation model of the İstanbul Channel, after each added block or principle, the model is debugged by the trace. In some large volume of output or complex cases trace element is limited with beginning time and ending time or conditions which are decided on through manual computation. Also the simulation program provides a command-oriented window to allow the interaction with the running simulation model by typing in commands at a prompt. These commands provide a powerful framework for monitoring and controlling the simulation run. They can be used to view and change the values of attributes and variables, examine the entities in a queue, obtain statistics on a resource, set break points in the model, and so forth. Thus events and activities at critical points in the model can be closely observed and tracked. In the model this command window is also used for verification purposes. Furthermore, the developed animation of the simulation model can also be used to observe the events and thus support the verification process. Especially the number of vessels waiting in the queues, number of idle or busy pilots and tugboats, service boats, the northbound and southbound lanes for transit vessels and overtaking lane animations are used for the verification of the model logic through animation.

After the verification of the model is completed and the model is run by the input data, the outputs are collected and the validation step is initiated.

The model structure and output should be plausible for any extreme and unlikely combination of levels of factors in the system. Therefore, extreme condition validations, which involve assigning extreme values to selected parameters and comparing the model-generated behavior to the anticipated behavior of the real system under the same extreme condition, are applied to the developed simulation model of the İstanbul Channel. Extreme condition validation consists of carrying out runs to simulate extreme situations and to verify that the model performs as intended in such situations. Hence, 95 per cent confidence intervals are calculated according to the results of ten replications. First of all, arrival rate of vessels is decreased and daily one vessel is sent to the system. After a two-day length run, the statistics show that number of vessels waiting in the queues and waiting times of vessels is zero. Also, waiting times and queue counters are checked for the case of very low interarrival times of vessels (assumed to be exponentially distributed with mean of one minutes). In this extreme case, the 95 per cent confidence interval for final value of vessels waiting in the queues is [571, 613] and 95 per cent confidence interval for average waiting time of vessels is [104, 133] minutes even after a 400 minutes length run. These output values are as high as expected from such a high frequency arrival profile.

The most definitive test of a simulation model's validity is to establish that its output data closely resemble the output data that would be expected from the actual system. After the simulation model of the existing system is developed, its output data are compared to those from the existing system itself. If the two sets of data are "close" to each other, then the model of existing system considered to be valid (Law and Kelton, 2000). Therefore the results of ten replications (run for four months) for the base model (where visibility is normal, pilot and tugboat availabilities are 15/6 respectively, the season is winter, no threshold is applied to any vessel, interarrival rate of the vessels and vessel profile are at the normal levels) and the statistics obtained from real data of year 2005 are compared for validation of the system. As the applications of some rules have been changed in last few years, the vessel profile is modified in order to better resemble the current practice, instead of changing the rule set. Accordingly, 78 per cent of arriving vessels are general cargo carrying vessels, 13 per cent are tankers, 6 per cent are HazMat carrying vessels and 3 per cent are passenger vessels in the modified vessel profile. According to the existing data, on the average 2068 southbound and 2115 northbound vessel passages are observed in a month. The 95 per cent confidence interval for the same responses are [2023.730, 2121.269] and [2043.890, 2166.709] where the confidence intervals contain the real values. Actual data regarding the number of vessels passing daily show that an average 70.5 vessels entered from south entrance and 68.9 vessels entered from north entrance in year 2005. Base run results demonstrate that the 95 per cent confidence interval for the northbound vessels is [68.129, 72.223] and for the southbound vessels is [67.457, 70.708] where the actual 2005 data lie in the intervals. Although the official reports do not give information about the average number of vessels waiting in the queues, the 95 per cent confidence interval of average number of vessels waiting in the queues (NaturalQ_N, NaturalQ_S and Common Queue) is [65.081, 86.478] where these values are reasonable and close to the conjectural values. Furthermore, historical data show that total waiting time at the end of April is 15.56 hours (933.6 minutes). Similarly, the 95 per cent confidence interval of the same response is [13.5, 18.13] (in hours). The 95 per cent confidence interval for the transit time of the vessels in ten replications is [116.193, 116.418]. Even though the real data of year 2005 do not give information about the exact transit time of the vessels, when the length of the Channel and the average speed of the vessels are taken into consideration, 100 minutes can be calculated (with the effects of the current and overtaking not being taken into account). Therefore, 116 minutes determined as the average transit time of the vessels is quite reasonable.

4.4 Outputs of the Model

The developed model is run for four months (between January and April for the winter season, between April and July for the summer season). Ten replications have been run for the base scenario. The internal random variate generation structure is used for the generation of input data. On the other hand, one replication has been run for other scenarios where various input factors are collectively and specifically arranged to predict the effects of increasing transit traffic demand (collectively or by vessel type and characteristics), adverse meteorological conditions, changes in the level of services provided (such as tugboats and pilot captains), and vessel class priorities can be better predicted. External file reading structure is preferred for these scenario runs.

The simulation runs provide two different monthly output files with respect to north and south entrances, both entrances, all vessels and each vessel type when the run is completed. The statistical values in the first output file are comprised of maximum, minimum, average values, standard deviations and 95 per cent confidence intervals of the following responses:

- Number of vessels in queue (still waiting for transit) at end of each month,
- Number of vessels that have completed their transit,
- Waiting time of vessels that have completed their Channel transit (aggregate of all vessels and by vessel type at each direction),
- Waiting time of vessels in queue (still waiting for transit) at the end of each month (by queue type),
- Transit time of vessels that have completed their Channel transit (aggregate of all vessels and by vessel type at each direction),
- Pilot captain and tugboat utilization (ratio of total busy time and total available time),
- Vessel densities (number of transit vessels per mile) in each zone and for the entire Channel (aggregate of all vessels and by vessel type).

All statistics are gathered and the average of the values at the end of the fourth month (end of the simulation period) is used in the output analysis.

Table 3. Factors and their levels

Factor	*Name*	*Low*	*Average*	*High*
A	Vessel Profile	Normal		HazMat High
B	Arrival Rate	Normal		High
C	Threshold	None	All Same	Different
D	Pilot / TugBoat	10 / 4	15 / 6	20 / 9
E	Visibility	Normal		Low
F	Season	Winter		Summer

The second output file is associated with the effects of meteorological conditions. It includes the number of vessels in each queue just before and after the fog occurrences in the simulation model. Therefore effect of the visibility level on the vessel passage can be better observed.

5 Results and Scenario Analysis

The analysis of the simulation runs is focused on the effects of six factors:

- Number of tugboats and pilots available,
- Transit vessel profiles (types),
- Transit vessel demand,
- Vessel priorities,
- Meteorological conditions at the Channel,
- Season.

These six factors and their different levels are chosen to form 144 distinct scenarios (including the base scenario). The outputs of the model are collected and analyzed through the Design Expert 6.0 software (Stat-Ease, 2004). The factors and their levels deployed in different scenarios are displayed in Table 3.

The levels of the factors are determined based on the historical data and expert interviews. For the visibility factor, the expected fog occurrences (257 hours) for four months (between January and April for winter season, between April and July for summer season) are doubled for the "high" setting. Pilot and tugboat availabilities have three settings; 10/4, 15/6 and 20/9, where 15/6 is the current level with 15 captain pilots and six tugboats on duty in each shift. For each setting there are 2 service boats on duty. Thresholds deployed also have three settings: in one setting no threshold is applied to any vessel; that is, any vessel reaching the top of the "Common Queue" gains the right of request a "barrier" activated at the opposite Channel entrance (to stop the entrance to the Channel of these vessels whose presence in the Channel would inhibits its own entrance) as long as visibility and day/night conditions are favorable. In the second setting, all vessels take the same threshold value proportional to the number of available pilot and tugboat resources. In the third setting, lower threshold values (thus higher priorities) are given to passenger vessels, and highest threshold values (thus lowest priorities) are given to tankers, LNG-LPG and hazardous cargo carriers (general cargo vessels are assigned medium threshold values). The threshold values are again assigned with respect to the available number of pilots and tugboats. The different levels of threshold values are decided via test runs and are tried to be balanced with the waiting time of the vessels related to other factors. Regarding vessel interarrival times, in the first setting, interarrival rates obtained from the statistics of year 2005 are deployed. In the second setting, all arrival rates are increased by 15 per cent. Regarding vessel profiles, in the first setting transit vessel profile observed in year 2005 is taken into consideration (which is shown in Table 2), but small modifications are done due to changes in rule applications as mentioned before. In the second setting, ratio of HazMat carrying vessels and tankers are increased to 10 per cent and 17 per cent respectively and ratio of general cargo carrying vessels are decreased to 70 per cent. Seasons deployed have two settings; where one setting is between January and April, while the second setting is between April and July.

Among these factors, meteorological conditions, seasons, transit vessel arrival rate and transit vessel profiles represent the uncontrollable factors which affect the transit traffic in the Channel. Number of pilot captains and tugboats and threshold values can be regarded as the factors that can be controlled by the Traffic Control Authority in order to improve maritime traffic conditions in the Istanbul Channel. Number of pilot captains and tugboats available is primarily a resourceing decision, while threshold values is a (vessel) sequence decision. In order to better understand the relative and absolute effects of uncontrollable/controllable factors a comparison of the selected 15 scenarios with the base model based on 8 response variables selected from the output files is given in Table 4.

The response variables selected are;

- Y1: Number of vessels that have completed their Channel transit,
- Y2: Average waiting times of vessels that have completed their Channel transit,
- Y3: Maximum waiting times of vessels that have completed their Channel transit,
- Y4: Average transit times of vessels that have completed their Channel transit,
- Y5: Average pilot captain utilization,
- Y6: Average tugboat utilization,
- Y7: Average number of vessels waiting in queues at the end of each month,
- Y8: Average transit vessel density in the Channel.

Table 4 shows that number of pilots and tugboats deployed has the highest effect on the responses. Also arrival rate of vessels has a higher effect than vessel profile. It also indicates the effect of applying different sequence decisions to the vessels. Applying different threshold values to the vessels rather than not applying any threshold value, makes an improvement in most of the performance measures.

Next, significant factors affecting the response variables are determined by analyzing ANOVA tables. In this regard, first contributions of the factors and their interactions are considered in order to identify and sequence the significant factors with respect to decreasing significance. The factors are added to the model one by one according to their contributions (factors having contributions less than 0.1 per cent are ignored in order to simplify the analysis) until the model F-value implies that the model is significant and R-Squared is higher than 99.00 per cent while adjusted R-Squared and Predicted R-Squared values are reasonable in agreement with each other. The important factors (where h denotes high level and l denotes low level of this factor), interactions of these factors and their effects (where + denotes an increase and - denotes a decrease) on responses are given in Table 5.

6 Further Studies

It is planned to expand the discussed simulation model of the maritime transit traffic in the İstanbul Channel by including considerations and processing capability to handle currents and wind conditions prevailing at the Channel. The effects of these new factors on vessel speeds, tugboat/pilot deployments, vessel pileups and in transit vessel densities should be of particular

Table 4. Comparison of scenarios with base scenario

Vessel Profile	Arrival Rate	Threshold	Pilot / Tugboat	Vessels Passed	Avg transit times	Vessel density	Avg waiting times	Max waiting times	Vessels in queues	Pilot utilizations	Tugboat utilizations
Normal	*Normal*	*all 0*	*15 / 6*	1	1	1	1	1	1	1	1
High	*Normal*	*all 0*	*15 / 6*	0.989	0.996	0.976	1.518	1.923	2.186	0.994	0.955
Normal	*High*	*all 0*	*15 / 6*	1.126	1.008	1.119	1.884	1.376	2.457	1.116	1.093
High	*High*	*all 0*	*15 / 6*	1.111	1.009	1.087	2.883	2.089	4.838	1.100	1.016
Normal	*Normal*	*all different*	*15 / 6*	1.001	0.997	0.999	0.856	0.871	0.756	1.001	1.004
High	*Normal*	*all different*	*15 / 6*	1.125	1.008	1.124	1.269	1.349	1.571	1.123	1.108
Normal	*High*	*all different*	*15 / 6*	0.981	0.994	0.975	1.449	1.694	1.756	0.996	0.965
High	*High*	*all different*	*15 / 6*	1.091	1.005	1.098	1.535	2.088	2.576	1.115	1.070
Normal	*Normal*	*all 0*	*10 / 4*	0.939	0.992	0.918	5.588	1.091	7.918	0.918	0.749
High	*Normal*	*all 0*	*10 / 4*	0.934	0.990	0.900	5.755	2.175	8.631	0.913	0.720
Normal	*High*	*all 0*	*10 / 4*	1.022	1.000	1.006	6.683	1.340	11.752	1.003	0.743
High	*High*	*all 0*	*10 / 4*	0.999	0.995	0.980	7.152	2.173	12.697	0.990	0.709
Normal	*Normal*	*all different*	*10 / 4*	0.960	0.987	0.952	2.339	1.365	2.876	0.945	0.875
High	*Normal*	*all different*	*10 / 4*	0.958	0.984	0.933	2.608	2.263	3.945	0.945	0.847
Normal	*High*	*all different*	*10 / 4*	1.035	0.994	1.051	3.170	1.617	5.019	1.043	0.907
High	*High*	*all different*	*10 / 4*	1.039	0.989	1.029	3.423	2.262	5.827	1.037	0.893

Table 5. Summary of important factors and their effects on responses

	Factors and Levels								
Responses	D_h	B_h	$B_h\ D_l$	$B_h\ D_h$	A_h	$A_h\ D_l$	E_h	F_h	C_h
Number of vessels passed	+	+		+	-	-			
Average waiting times of vessels	-	+	+		+	+	+		-
Maximum waiting times of vessels	-	+	+		+	+	+	-	
Average transit times of vessels	+	+		+	-	-	+	-	-
Average pilot utilizations	-	+			+				
Average tugboat utilizations	-	+	+		-		-		
Average number of vessels in queues	-	+	+		+	+	+	-	
Average vessel density	+	+		+	-	-			

interest. Also some modification of the current model (regarding the implementation of Rules and Regulations) is planned, as the applications of some rules have been changed in last year. Finally parametrization of pursuit distances of vessels in transit (i.e. modeling capability to experiment with different pursuit distances - other than eight cables) is to be accomplished.

Moreover, it is expected that this model will provide a platform for a comprehensive risk management and analysis study of the İstanbul Channel. In this regard, a dynamic risk profile is planned to be determined for various regions (substations) along the Channel. The risk profile of a region will be dependent on the accident possibility of that region (based on the region's, morphological conditions, local traffic density, visibility, current & wind conditions) and "potential negative impact" propensity of that region (based on the region's population, real estate holdings and cultural heritage and richness, which are all to be accounted for and estimated using a decreasing scale from shoreline to a depth of 1 km). The dynamic nature is expected to come from varying effect of random wind, visibility and current realizations both on the "accident possibilities" and on the "size of the effected region". Then, it is planned to have the transit vessels in the Channel "pick up" additional risks at each station (as they move along the Channel), depending on the dynamic risk profile of each station visited and the vessels own characteristics, such as its type, length, age, draft etc. Thus the risk management of accidents and the results of them in terms of culture, environment and human life will be achievable in further studies.

7 Conclusion

In this study a functional simulation model for the maritime transit traffic in the İstanbul Channel is discussed. This simulation model provides a powerful and practical platform to determine and test the effectiveness of various policies and decisions related with the control and management of the transit traffic in the Channel. It is based on the official Traffic Rules and Regulations governing the flow of traffic in the Channel, but at the same time relies heavily on historical data and past experience, within the framework of scenarios regarding different meteorological conditions and transit traffic demand and profile. The policies and decisions investigated are related with transit vessel priorities, service (tugboats and pilot captains) availabilities; various interpretations and implementation issues related with the Channel Traffic Regulations can also be investigated through this model.

The effect of these factors on number of vessels passed, average waiting times of vessels, maximum waiting times of vessel, average transit times of vessels, average pilot utilization, average tugboat utilization, average number of vessels waiting in the queue, maximum number of vessels waiting in the queue and average transit vessel density throughout the Channel are investigated and the most significant factor is determined as number of pilots and tugboats in the service, while the second effective factor is the arrival rate of vessels. After the effects of factors D and B, their interaction is also influential on the responses. Scenario analysis show that, one of the most important factors is the interaction of factors A and D after the effect of vessel profile. Moreover, the effects of factor visibility and threshold value, are also quite interesting as can be seen in Table 5.

Additionally, selected 15 scenarios and their comparison with the base scenario demonstrates the effects of factors and their interactions. Table 4 principally shows the effect of applying different threshold values to vessels ,(which provides different sequencing of the vessels in the queues) and changing the number of pilot captains and tugboats. As the model is intended to support the Channel Traffic Control System, examining these factors besides the uncontrollable factors such as vessel arrivals or profiles, have benefits to the decision makers.

Acknowledgements

The authors gratefully acknowledge the support of TUBITAK - Turkish Technological and Scientific Research Institute, in this research, through Research Project 104Y207.

References

Franzese, G. L. A., Abdenur, L. O., Botter, C. R., Starks, D. and Cano, R. A. (2004), "Simulating the Panama Canal: Present and Future", 2004 Winter Simulation Conference, Orlando, Florida, USA, 1835–1838.

Köse, E., Başar, E., Demirci, E., Güneroğlu, A. and Ş. Erkebay (2003), "Simulation of Marine Traffic in İstanbul Strait", *Simulation Modelling Practice & Theory* 11, 597–608.

Law, A. M. and Kelton, W. D. (2000), *Simulation Modeling and Analysis*, McGraw-Hill Press, Singapore.

Official Gazette (1998), *Traffic Regulations for the Turkish Straits, 8 October 1998*, 23515, Official Gazette, regulation No: 98/11860.

Or, İ. and Tayanç, D. (2003), "An Expert Judgment Based Study of Accident Risk in the İstanbul Channel", 3rd International Conference on Oil Spills, Oil Pollution & Remediation, MEDOSC'2003, Boğaziçi University & University of Manchester, İstanbul.

Otay, N. E. and Özkan, Ş. (2003), "Stochastic Prediction of Maritime Accidents in the Strait of İstanbul", 3rd Intl. Conf. on Oil Spills in the Mediterranean and Black Sea Regions, İstanbul, 55–64.

Öztürk, B. (1995), "The İstanbul Strait, A Closing Biological Corridor", in: I. Soysal (ed.), "*Turkish Straits, New Problems, New Solutions*", ISIS, 145–154.

Rockwell Software (2004), Template Developer's Guide Arena 7.0 [Manual]. Milwaukee, WI, USA.

Stat-Ease (2004), Design Expert 6.0 [Manual]. Minneapolis, MN, USA.

STRA (1999), "İstanbul ve Çanakkale'den Geçiş Yapan Gemilerle İlgili İstatistikî Bilgi ve Değerlendirmeler", Technical Report, Sea Traffic Regulation Administration.

Tan, B. and Otay, E. N. (1999), "Dynamic Determination of the Safest Navigation Route for Transit Vessels in the Strait of İstanbul", *Naval Research Logistics* 46, 871–892.

TBLKKD (2005), "Turkish Straits", Retrieved July 8, 2005, from Straits and Ports Maritime Pilots' Association Website: http://www.tblkkd.org.

VTS (2005), "Turkish Straits VTS User's Guide", Retrieved July 8, 2005, from General Management of Coastal Safety and Salvage Administrations Website: http://www.turkishpilots.org.

Yazıcı, M. A. (2004), "Dynamic Determination of the Safest Navigation Route for Transit Vessels in the Strait of İstanbul", M.S. Thesis, Boğaziçi University, Institute for Graduate Studies in Science and Engineering.