INVESTIGATION OF TRANSIT MARITIME TRAFFIC IN THE STRAIT OF ISTANBUL THROUGH SIMULATION MODELING AND SCENARIO ANALYSIS

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Abstract: This study aims to develop a functional simulation model for the maritime transit traffic in the Strait of Istanbul and to perform scenario analysis to investigate the effects of type and frequency of transit demand, as well as various natural factors, resources and decision / policy rules, on the system. In this regard, the Strait traffic rules and regulations, transit vessel profiles, pilotage and tugboat services, meteorological and geographical conditions are considered in the model to provide a platform to analyze the effectiveness of various policies and decisions related to the transit traffic in the Strait of Istanbul. The statistics tracked and collected in the analysis are the number and types of vessels passed, transit times of vessels, vessel densities throughout the Strait, waiting times of vessels, pilot and tugboat utilizations. In the first phase of the study, scenario analyses have been designed and accomplished to investigate the effects of vessel profiles, vessel arrival rates, vessel priorities, pilot and tugboat availabilities and visibility conditions. In the second phase, the analyses are extended by integrating probabilistic current and visibility submodels, comprehensive overtaking rules, parameterization of pursuit distances and other administrative controls (regarding vessels in transit in the Strait). The results obtained are reported.

Keywords: Simulation, Strait of Istanbul, Maritime traffic, Arena®

INTRODUCTION

The Turkish Straits (the Strait of Istanbul and the Strait of Çanakkale), which have narrow and winding shapes that give them the resemblance of a river, are actually one of the most strategically important waterway systems in the world. Their hard to navigate geographical properties, cross continental bridges and energy transfer lines, meteorological conditions, dense and increasing transit and local traffic, vessel and cargo characteristics, make the Straits' traffic conditions quite complex and risky.

Geographically, the Strait of Istanbul (Figure 1) is one of the narrowest waterways in the world. Its length is 31 kilometers, and its average depth is 45 meters. Its average width is 1.5 km, with this width decreasing to 700 meters at its narrowest point (Anadoluhisarı - Rumelihisarı).

The natural and non-natural factors affecting the safety of transportation in the Strait, as well as the accidents occurred in the past, have required some stringent rules and procedures for transit vessels (called the Turkish Straits' Maritime Traffic Regulations and which will be denoted as "R&R" throughout this article) and a sophisticated Vessel Traffic Control and Monitoring System (VTS). The vessels arriving at the North or South entrance of the Strait of Istanbul enter the Strait according to the directions of VTS, which uses strict and well defined regulations, rules and all other data that are received by radars, sensors and stations. The primary mission of the regulations and the VTS is to reduce the maritime transportation risks in the Strait [VTS Users' Guide].

Figure 1: The Strait of Istanbul

The objective of this study is to create a functional simulation model (based on the mentioned Rules and Regulations) for transit vessel traffic in the Strait of Istanbul, to provide a realistic and practical environment, in which to speedily analyze and evaluate the effects of policies, resource availabilities, possible transit vessel profiles and environmental conditions, based on past transit vessel and environmental conditions data. In other words, the aim is to obtain a platform to analyze all rules, procedures and natural conditions affecting the status of Maritime Traffic in the Strait of Istanbul. This platform should also be deployable as a tool to support real time decision making at the Strait Traffic Control Authority.

MODEL FORMATION AND OBJECTIVES

The maritime traffic model developed includes the following major components:

- Randomized vessel arrivals at the North and South entrance of the Strait,
- Randomized vessel types and characteristics,
- Straits' Traffic Rules and Regulations (R&R),
- The pilotage and tugboat services (with predetermined and parameterized capacities),
- Randomized meteorological conditions of visibility and current,
- Two main traffic lanes, one overtaking lane and integrated overtaking rules.

In line with the study objectives, the simulation model developed realistically reflects the conditions influencing the behavior of transit vessels in the Strait, and thereby correctly mimics the flow of transit traffic itself. Scenario analysis has been another intended objective. The levels of various input factors are collectively arranged into 'scenarios' and it is possible to study and compare the results of different scenarios [Almaz, 2006].

Via scenario analysis,

- The effects of increasing transit traffic demand (collectively or by vessel characteristics and type), adverse meteorological conditions, changes in the level of services provided (such as tugboats and pilot captains), and vessel class priorities, can be better predicted,
- The effects of various interpretations and changes in the application of Traffic Rules and Regulations can be investigated,
- By experimenting with different vessel prioritization schemes, the waiting times of vessels (or certain types of vessels), dangerous pile ups (of waiting vessels), undesirable transit vessel densities (especially in critical parts of the Strait) can be tried to be reduced. The causes of unusual delays can be identified and alternative solutions proposals can be experimented on,
- The pilot and tugboat issues can be further elaborated as follows. The number of pilot captains and tugboats available is one of the main factors that cause delay for those vessels that need them. So, determining their availability target levels and expected utilization at those levels for a given level of transit traffic demand is quite important. Equally important is the capability to track the required change in pilot and tugboat target levels, as a function of changing transit traffic demand.

The simulation model is specifically designed to handle these issues.

MODEL STRUCTURE

The simulation software Arena 9.0 is used for the development of the simulation model of Maritime Transit Traffic in the Strait of Istanbul (figure 2).

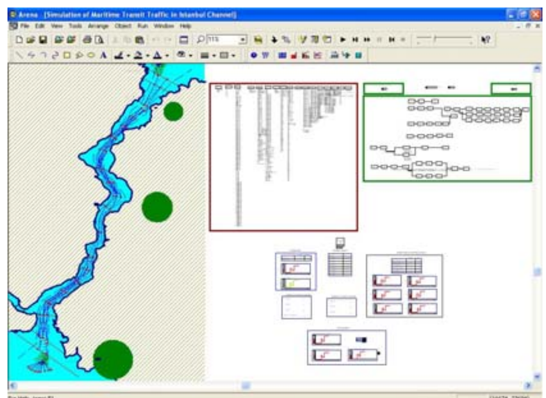

Figure 2: Simulation model in Arena 9.0

The input data of the system can be listed as: transit vessels' types, lengths, speeds, anchoring durations, pilot and tugboat demands, visibility and current conditions. 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 or the input data can be read from the text files. The reason for this flexibility is that internally generated input data allows for better control of the parameters during scenario analysis and facilitates the independent replication of simulation runs to analyze the effects of randomness. On the other hand, the external input of data allows for the deployment of the model as a real time decision support tool for the Strait Traffic Control Authority.

Three classes of control parameters (which are: external and internal parameters, the R&R) are used in order to clarify the logic of the model and to simplify scenario analysis. External parameters (those parameters which can not be controlled by the

Strait Authority) can be summarized as meteorological conditions, transit vessel profile, arrival rate, speed capability and pilot captain/tugboat requests. Available number of pilot captains and tugboats, transit vessel priorities and overtaking rules, are the internal parameters of the model (these are the parameters which can be controlled by the Strait Authority). The third class is the R&R (which is regarded as unchangeable throughout this study).

MODEL LOGIC AND FLOW

The simulation model of the transit traffic in the Strait of Istanbul is based on the R&R. Various experiences of the transit vessels, from approach to the Strait until departure from the region, including anchoring, waiting (due to nighttime, visibility, adverse current conditions, pilot / tugboat availabilities or rule restrictions) and transition conditions such as overtaking opportunities, current effects and pursuit distances are all incorporated in the integrated simulation model.

Vessel Types

The vessel types considered in the model are Passenger Vessels, LNG-LPG Carrying Vessels, Hazardous Material (HazMat) Carrying Vessels, Tankers and General Cargo Carrying Vessels. On the other hand, the R&R have classified all vessels into 11 “treatment classes”, based on their types, lengths and drafts (in a way reflecting the vessels’ sensitivity, potential risk and special needs). These classes which are displayed in table 1 are also deployed in the simulation model.

Table 1: Vessel classes

<table>
<tr><th></th><th></th><th colspan="5">Type</th></tr>
<tr><th>Length (m.)</th><th>Draft (m.)</th><th>Tanker</th><th>LNG-LPG</th><th>HAZMAT</th><th>Gen Cargo</th><th>Passenger Vessels</th></tr>
<tr><td>< 50</td><td>< 15</td><td rowspan="2">T1</td><td colspan="2" rowspan="3">L2</td><td rowspan="3">G2</td><td rowspan="6">PA</td></tr>
<tr><td>50 - 100</td><td>< 15</td></tr>
<tr><td>100 - 150</td><td>< 15</td><td>T2</td></tr>
<tr><td>150 - 200</td><td>< 15</td><td>T3</td><td colspan="2">L3</td><td rowspan="3">G3</td></tr>
<tr><td>200 - 250</td><td>< 15</td><td colspan="3">T4</td></tr>
<tr><td>250 - 300</td><td>> 15</td><td colspan="3">T5</td></tr>
<tr><td>> 300</td><td>> 15</td><td colspan="5">T6</td></tr>
</table>

In the random generation of the input factors, the arrival process of the transit vessels is based on the year 1999 statistics regarding vessel arrivals to the Strait of Istanbul. Attributes of the vessels that are used in the arrival process are interarrival times, entrance direction, ship type, length, draught, speed, anchoring duration, pilot demand and tugboat demand. Interarrival times of the vessels are derived from average daily vessel transits. In the transit data of 1999, the average number of daily vessels transits through the Strait is given as 131 (in both directions). Based on this statistic, interarrival times are assumed to be exponentially distributed with mean of 21.98 minutes for North and South entrances throughout whole day. The remaining attributes of the vessels are generated through empirical probability distributions based on the 1999 data. Particularly, the speed of vessels is assumed to be uniformly distributed between 10-12 knots for passenger vessels, 8-12 knots for Tankers, LNG-LPG and Hazardous Material carrying vessels and 8-10 knots for general cargo carrying vessels.

The Strait Entrance

The (randomly) arrived vessels first enter the anchoring area according to their request and remain there through their anchoring durations. Those who do not anchor or leave their anchoring area are ready to enter the Strait. At that point ‘Ready Time’ and ‘Threshold’ attributes are assigned to those vessels. Ready Time is the vessel attribute which is used to determine its place (ordering) in the waiting queue, while Threshold is the attribute that determines the vessel's priority (in the sense that the Strait Authority puts a ‘Barrier’ to the opposite Strait entrance, once a vessel has waited an amount of time defined by its Threshold value). Such a barrier stops the entrance to the Strait from the opposite side, of any vessel, whose presence in the Strait would hinder the entrance of the vessel waiting for the appropriate conditions. Note that, it is still possible for a vessel to enter the Strait without putting up a barrier, if it is at the queue head (with respect to Ready Times) and there are no vessels in transit, whose presence hinder its entrance.

All vessels wait in ‘Common Queue’ and check if the Strait is available and safe for the passage. Each vessel in the ‘Common Queue’ first checks for the satisfaction of the R&R with respect to the existing traffic in the Strait. When there is no such restriction, other R&R requirements, such as pilot and tugboat needs, visibility, current level and daylight restrictions (according to the R&R, certain types of vessels may sail the Strait only in daylight) are checked, with respect to vessels type, length and conditions. If all factors are suitable and services are available, then the vessel enters the Strait. This process is sequentially followed for all vessels in the ‘Common Queue’.

The Strait

In the Strait, a vessel passes through eight different zones [Or and Kahraman, 2002]. Each zone is divided into a sequence of ‘stations’ which are set at a distance of 8 cables (0.8 nautical miles ≈ 1.482 km.) from one another. Also, each station is comprised of 4 ‘substations’, which are 2 cables distance from one another. Thus, the Strait is represented on 21 stations or 84 substations to cover a distance of 16.8 nautical miles. This is to satisfy the R&R requirement that vessels in transit in the Strait shall maintain a certain pursuit distance between one-another. This distance is actually a control parameter of the Strait Authority and is also deployed as such in the model [Almaz, 2006]. According to a strict interpretation of the R&R and in the base settings, this pursuit distance is 8 cables.

Overtaking

As mentioned, the simulation model provides three traffic lanes for transit vessels along the Strait (one northbound lane, one southbound lane and an additional lane for overtaking, wherever it is allowed). Since the R&R do not allow overtaking in the Kandilli region (i.e. at the narrowest section of the Strait, between Vaniköy and Kanlıca), in the model the overtaking lane is removed at this region.

The overtaking rules implemented in the model are as follows: Whenever a vessel is faster than the one ahead, it checks three conditions,

i) that there will be no vessels in the overtaking lane from the opposite direction, until the expected completion of its overtake,
ii) that the closest vessel in the overtaking lane traveling in the same direction is at least "the pursuit distance" away,
iii) that it is fast enough to complete the attempted overtake before it reaches the Kandilli region.

Pilotage and Tugboat Services

The pilot captain and tugboat needs of the vessels about to enter the Strait are also taken into consideration. In the model, if a vessel prefers (or is required by the R&R) to use any of these services, it seizes them at the designated embarking and disembarking areas at the North and South entrances of the Strait (the associated vessel's transit through the Strait is delayed by a certain amount of time to cover the vessel's slowing down and speeding up during the embarking / disembarkation activity).

Additionally, two control mechanisms are included in the model to increase the utilization of pilots and tugboats. At any entrance, while the pilot or tugboat is released, if the number of idle pilots or tugboats is higher than or equal to predefined limits, the excess pilot or tugboat is transferred to the opposite side in 30 minutes and 90 minutes respectively (time allowed for deadheading). Also, when a pilot or tugboat is seized, the number of remaining resources is checked. If the number is zero and the other side has more than two of that resource idle, these are sent to the side in need. During the transfer of excess pilot and tugboat, the 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 Strait, it releases the pilot or tugboat at the disembarking area; the released pilot or tugboat is then designated to be an additional available resource at the release station.

The Visibility

The R&R impose that: "when visibility drops to 1 mile or less in any area within the Strait, vessel traffic shall be permitted in one direction only. In such situations, vessels carrying hazardous cargo, and large vessels shall not enter the Strait. When visibility drops to less then 0.5 mile, vessel traffic shall be suspended in both directions."

As mentioned before, in the model, daily visibility values can be either externally inputted or internally generated (with respect to a probability distribution based on historical data).

The statistical analysis of past visibility data has shown a strong seasonal pattern (low visibility levels are far more frequent in Winter). The moving average of 31 days, regarding the fog occurrence frequencies of calendar days is displayed in figure 3 (this statistic is based on the actual number of fogs observed on each day in the past 17 years). Accordingly, three probability distributions (corresponding to three distinct seasons) are developed to govern the random generation of daily visibility conditions throughout the Strait. The Summer (June, July, August and September) and transition seasons (May and October) are based on empirical distributions. The Winter season is based on an on/off process and is modeled through a phase type distribution [Altıok, 1996]. In this on/off process the system state alternates between the on state and the off state successively. The on state signifies good visibility conditions, whereas the off state signifies bad visibility conditions. The lengths of these on/off periods are approximated by "Mixtures of Generalized Erlang" (MGE) distributions [Almaz, 2006].

The Current

The Strait of Istanbul is influenced by four different current formations.

- Southbound surface current caused by the 20 cm altitude difference between the Black Sea and the Aegean Sea,
- Northerly deep current caused by the lower density of the Black Sea compared to the density of the Aegean Sea,
- Eddies, regional counter currents formed due to the geographical features of the Strait,
- Orkoz, the reverse surface current, caused by the strong southerly winds.

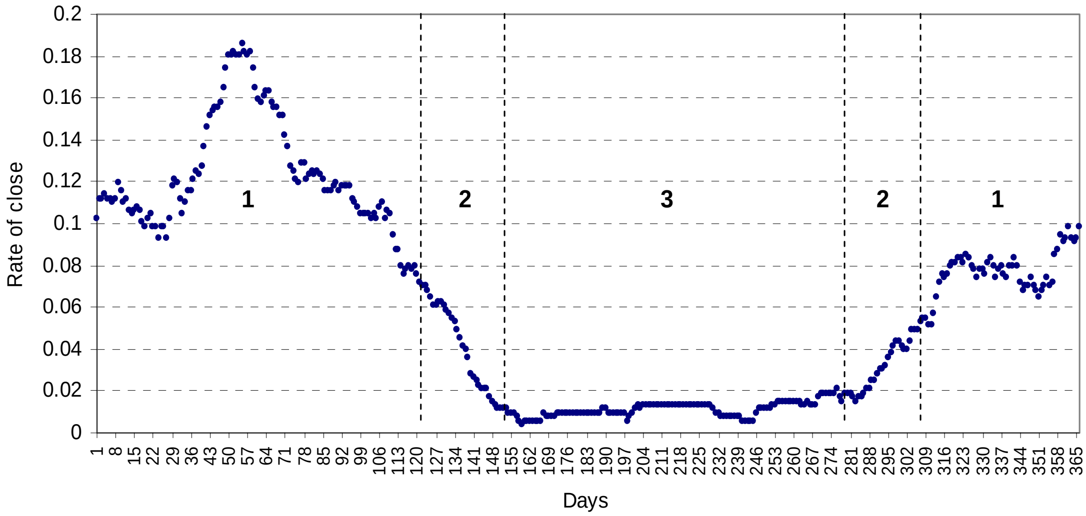

Figure 3: Frequency distribution of daily fog occurrences over 17 years – moving averages of 31 days (Source: Kandilli Observatory and Earthquake Research Institute)

In this study, the southbound surface current, which is the main current regime in the Strait, and the reverse surface current are taken into consideration.

The Strait features a north to south surface current almost at all times. This current attains its peak value at the narrowest point of the Strait, while tapering off to around 90% of the peak value at the two entrances. The peak current value varies probabilistically between 0 to 6 knots with a mean about 2.7 knots. Naturally, this current affects the realized speed of transit vessels (speeding up the southbound vessels and slowing down the northbound ones). Additionally, vessels which may experience navigation problems at higher current levels are either assigned tugboats to aid them or are not allowed in the Strait until conditions improve. These factors are incorporated into the model through vessel speed alterations (due to current), tugboat assignments and/or vessel entrance denials.

Current values throughout the Strait are determined through the random generation of a daily peak value, which is then reflected to the whole Strait via appropriate predetermined percentage factors for each substation in the model. Both the probability distribution of the peak value (which is based on an autoregressive forecasting model) and the percentage factors are determined based on historic current data [Almaz, 2006].

VERIFICATION AND VALIDATION

For verification purposes, the modeling is accomplished in stages where each additional stage is individually debugged and tested. Next, additional subprograms and levels of detail are added and debugged successively until a model is developed that satisfactorily represents the system under study. Within this context, the "tracing" technique of discrete-event simulation is deployed. 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 occurrence and compared, through manual calculations to see if the program is operating as intended [Law and Kelton, 2000]. In this study, after each added block or principle, the model is debugged by the trace. Furthermore, the developed animation of the simulation output can also be used to observe the events and thus support the verification process. The observation of the vessel behavior in entering, proceeding in and exiting the primary and overtake lanes are especially supportive for the verification of the model logic through animation.

For validation purposes, 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.

A key validation step for a simulation model is to establish that its output matches the behavior that would be expected of the actual system. Therefore, the results of 10 simulation (run) replications (each covering the same four month period) for the base scenario (whose Strait vessel traffic and meteorological condition data is based on the year

1999 data and statistics) are compared to the corresponding actual data, for validation purposes. Past data shows that, on average, 3930 monthly vessel transits have occurred in 1999. In the model output, the 99% confidence interval for this response variable (based on the simulation runs) is [3864.49, 3929.11]. On the other hand, in the test runs of the simulation model, the 99% confidence intervals for the average number of vessels waiting in queues and for the of average waiting times of all vessels (in minutes) are obtained as [28.77, 32.99] and [177.09, 195.87], respectively. Unfortunately, there is no hard, specific data on the actual number of vessels waiting in the queues and their waiting times. Nevertheless, the corresponding values generated by the test runs seem reasonable and close to the conjectural values of the real system.

MODEL OUTPUT

Each simulation run generates two monthly output files with respect to the North and South entrances, total entrances, all vessels and each vessel type. The statistical values in the first output file are comprised of maximum, minimum, average values, standard deviations and 95 percent confidence intervals of the following responses;

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

Another 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 runs. Accordingly, the effect of the visibility level on the vessel traffic can be better observed.

RESULTS OF THE BASIC MODEL

Various experimental simulation runs have been accomplished for the basic model (i.e. the one in which the stochastic current and visibility submodels, comprehensive overtaking rules and parameterized pursuit distances have not yet been deployed).

The analysis regarding the basic model simulation runs is focused on six factors. These factors and their levels deployed in different scenarios are displayed in table 2.

Table 2: Factors and 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

These six factors and their different levels are chosen to form 144 distinct scenarios (including the base scenario). In the settings of the reference (base) scenario vessel profile and arrival rate is normal, no threshold (or priority) is applied to any vessel, pilot and tugboat availabilities are 15/6 respectively, the visibility is normal (106 hours according to the 1999 statistics) and the season is Winter.

In this regard, 10 replications of the reference scenario are run for four months (between January and April for the Winter season, between April and July for the Summer season). Additionally, one replication has been run for the other scenarios.

Table 3: Comparison of selected scenarios of the basic model with the base scenario

Vessel Profile	Arrival Rate	Pilot / Tugboat	*Number of vessels passed*	*Avg transit times of vessels*	*Vessel density in the Strait*	*Avg waiting times of vessels*	*Max waiting times of vessels*	*Number of vessels in queues*	*Pilot utilizations*	*Tugboat utilizations*
Normal	***Normal***	***15 / 6***	1	1	1	1	1	1	1	1
High	***Normal***	***15 / 6***	0.990	1	1	1.656	1.425	1.561	1.036	1.003
Normal	***High***	***15 / 6***	1.142	1.007	1.155	1.653	1.489	1.879	1.151	1.151
High	***High***	***15 / 6***	1.152	1.008	1.138	5.957	3.216	6.305	1.187	1.131
Normal	***Normal***	***10 / 4***	0.975	0.995	0.966	10.566	5.718	9.757	1.456	1.381
High	***Normal***	***10 / 4***	0.951	0.992	0.948	19.393	12.311	19.043	1.463	1.262
Normal	***High***	***10 / 4***	1.076	1	1.069	24.239	14.363	29.338	1.604	1.380
High	***High***	***10 / 4***	1.052	0.997	1.052	31.514	19.685	40.174	1.622	1.265

In order to analyze the effects of these factors, the response variables in the output files are deployed. The significant factors affecting the response variables are determined by analyzing ANOVA tables through the Design Expert 6.0 software. The important factors, the interactions of these factors and their effects on the responses are also investigated.

According to the results obtained, the most significant factor seems to be the number of pilots and tugboats in service, while the second most influential factor is the arrival rate of vessels. Table 3 summarizes some of the key results obtained. In this table, some selected scenarios are displayed in order to compare the effects of vessel profile, arrival rate and pilot / tugboat availability on the output values, when threshold, visibility and season factors are fixed at their reference scenario settings. Further results and discussions regarding the basic model simulation runs can be found in [Özbaş, 2005].

RESULTS OF THE INTEGRATED MODEL

In the second phase, the basic model and analysis are extended, by integrating probabilistic current and visibility submodels, comprehensive overtaking and encountering rules and parameterizing pursuit distances of vessels in transit in the Strait. Experimental simulation runs of the integrated model have focused on four additional factors and their effects on the output statistics. Some new scenarios considered and investigated, based on the levels of these factors, are displayed in table 4.

Table 4: Additional factors and levels

Factor	*Name*	*Low*	*High*
A	Current Profile	Normal	High
B	Kandilli Encounter Rule	Normal	Conservative
C	Vessel Pursuit Distance	4 cables	8 cables
D	Season	Winter	Summer

As mentioned before, the current profile in the Strait depends on a randomly generated peak current value, whose mean is taken as 2.7 knots for the 'Normal' setting, and as 3.5 knots for the 'High' setting.

The Kandilli encounter rule reflects an important R&R. According to this rule, certain types of vessels are not allowed to come across in the Kandilli region (in order to reduce high risk encounters in this critical region). However, since the exact speed of the vessels in the Strait are hard to predict, this rule needs to be applied within a safety factor. In the 'Normal' setting of the safety factor, Strait entry times of the vessels are regulated, so that potentially undesirable encounters (based on expected transit speeds) will not take place within 2 stations in each direction of the Kandilli region. While in the 'Conservative' setting of the safety factor, potential undesirable encounters are avoided within 4 stations in each direction of the Kandilli region.

Vessels in transit have to maintain a pursuit distance of at least 8 cables throughout the Strait. This distance is designed as a parameter in the integrated model and can vary between 2 cables to 10 cables. In the scenario analysis 4 cables and 8 cables settings are used.

Seasons are important since the randomness in the visibility condition is modeled in a seasonal pattern.

For the scenario analysis of the integrated model, 16 simulation runs (corresponding to the 16 combinations of the considered factors), each having four months duration, are executed with one replication. The reference scenario setting is determined as normal current profile, conservative setting of the Kandilli rule, 8 cables pursuit distance and Summer season. The effects of the factors are observed on 8 response variables, which are selected from the output files and comparisons with the base scenario are reported.

For the reference scenario, the average transit time of all vessels is 122 minutes, which is about 106 minutes for southbound and 138 minutes for the northbound traffic. A total of 15457 vessels passed though the Strait, with a daily average of 129. Pilot utilization is about 29% and tugboat utilization is about 51.5%. There are on average 64 vessels waiting in the queues.

The worst scenario occurs at the settings of high current profile, conservative implementation of the Kandilli rule, 8 cables pursuit distance and Winter season. The average transit time increases to 125 minutes with total vessels passed being 15282 and average number waiting in the queues being 106. Besides, average waiting time increases by 67%.

On the other hand, the best scenario occurs at the settings of normal current profile, normal implementation of the Kandilli rule, 4 cables pursuit distance and Summer season. In this scenario the average transit time decreases to 119.5 minutes with a total of 15560 vessels passing. The average number of vessels waiting in the queues decreases to 26, while the average waiting time decreases by 58%.

In order to analyze the effects of these factors on the selected response variables, Design Expert 7.0 software is used. The percentage contributions of the significant factors to explain the variation of the responses between scenario runs are given in table 5. The directions of the effects are also noted, such that "+" denotes an increase and "–" denotes a decrease. Table 5 points out the positive and negative influence of factors on output statistics. For example, 64% of the variation in the number of vessels passed is caused by the change in season.

Table 5: Important factors and their effects

Responses / Factors	Current	Kandilli Rule	Pursuit Dist.	Season
Number of vessels passed	- 1%	- 21%	- 10%	+ 64%
Avg transit times of vessels	+ 63%		+ 34%	
Vessel density in the Strait	+ 70%		+ 25%	+ 4%
Avg waiting times of vessels	+ 8%	+ 61%	+ 11%	- 15%
Max waiting times of vessels	+ 17%	+ 23%	+ 18%	- 23%
Number of vessels in queues	+ 7%	+ 63%	+ 11%	- 13%
Pilot utilizations	+ 64%		+ 28%	+ 6%
Tugboat utilizations	+ 39%	- 11%	+ 13%	+ 34%

It can be observed that, in the integrated model, each factor has varying importance on different aspects. For example, the Current mostly affects the transit time and the density in the Strait and through these, the pilot and tugboat utilization as well. The Kandilli rule has most influence on waiting times and on the number of vessels in queues. The Pursuit distance is effective on all of the responses, while the Season mainly affects number of vessels passed.

In table 6, the output values of various scenarios of the integrated model are compared to the base settings. These comparisons enhance the understanding of factors' effects on the output values and reveal some interesting implications of the model's results.

CONCLUSION

In this study a simulation model of the maritime transit traffic in the Strait of Istanbul is discussed. First the results of the basic model are summarized, then, the results of an integrated model are presented, via scenario analysis.

The results of the scenario analysis on the basic model indicate the importance of pilot and tugboat availability, arrival rate of vessels and vessel profiles. On the other hand, the results of the scenario analysis on the integrated model demonstrate the important effects of some external conditions (such as current and visibility) on the transit traffic. That is the number of vessels passed is mostly affected by the visibility conditions and the average transit time of the vessels is mostly affected by the current. Additionally, the impact of some control parameters (such as the Kandilli encounter rule and the pursuit distances) on the system is also quite important. The average waiting time of vessels is mostly affected by the Kandilli rule, while the pursuit distance has very significant effects on all of the output variables.

Through the results obtained, the study has also shown that adverse meteorological conditions combined with major increases in transit traffic and changes in vessel profile could lead to very undesirable traffic congestions and thus, increased risk in the Strait. On the other hand, the management and control tools available to the Strait Traffic Authority can be very much effective in managing these congestions and risks.

FURTHER STUDIES

The study continues with refinements and updating of the R&R, the vessel profiles and arrival distributions in the integrated model. An extended scenario analysis will be performed on the integrated model, aiming at a comprehensive investigation of all factors affecting the transit traffic system. Moreover, it is expected that this model will provide a platform for a comprehensive risk management and analysis study of the Strait of Istanbul.

Table 6: Comparison of all scenarios of the integrated model with the base scenario

Current Profile	Kandilli Rule	Pursuit Distance	Season	*Number of vessels passed*	*Avg transit times of vessels*	*Vessel density in the Strait*	*Avg waiting times of vessels*	*Max waiting times of vessels*	*Number of vessels in queues*	*Pilot utilizations*	*Tugboat utilizations*
Normal	***Normal***	***8 cables***	***Winter***	1	1	1	1	1	1	1	1
High	***Normal***	***8 cables***	***Winter***	0.999	1.024	1.023	1.139	1.744	1.123	1.022	1.020
Normal	***Conservative***	***8 cables***	***Winter***	0.995	1.003	0.997	1.755	1.433	1.845	0.995	0.981
High	***Conservative***	***8 cables***	***Winter***	0.991	1.025	1.016	2.248	1.772	2.324	1.016	1.004
Normal	***Normal***	***4 cables***	***Winter***	1.001	0.985	0.985	0.808	0.844	0.796	0.985	0.984
High	***Normal***	***4 cables***	***Winter***	1.002	1.006	1.008	0.949	1.024	0.910	1.006	1.004
Normal	***Conservative***	***4 cables***	***Winter***	0.998	0.988	0.985	1.464	1.153	1.527	0.982	0.968
High	***Conservative***	***4 cables***	***Winter***	0.998	1.009	1.008	1.708	1.567	1.716	1.003	1.000
Normal	***Normal***	***8 cables***	***Summer***	1.008	0.997	1.004	0.741	0.966	0.748	1.005	1.018
High	***Normal***	***8 cables***	***Summer***	1.007	1.019	1.025	0.867	0.927	0.869	1.028	1.036
Normal	***Conservative***	***8 cables***	***Summer***	1.002	1.000	1.002	1.345	1.302	1.398	1.002	1.004
High	***Conservative***	***8 cables***	***Summer***	1.001	1.024	1.025	1.776	1.257	1.838	1.027	1.025
Normal	***Normal***	***4 cables***	***Summer***	1.009	0.980	0.989	0.569	0.754	0.565	0.990	1.000
High	***Normal***	***4 cables***	***Summer***	1.009	1.001	1.010	0.693	0.811	0.681	1.011	1.022
Normal	***Conservative***	***4 cables***	***Summer***	1.008	0.985	0.993	0.905	0.793	0.926	0.991	1.000
High	***Conservative***	***4 cables***	***Summer***	1.005	1.007	1.013	1.339	1.284	1.372	1.011	1.014

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