SIMULATION OF THE VESSEL TRAFFIC SCHEDULE IN THE STRAIT OF ISTANBUL

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ABSTRACT
In this study, a simulation model is developed via the Arena 11.0 software to mimic the actual Istanbul Strait vessel flow under the established traffic regulations and meteorological conditions. The established practice of uni-directional daytime and two-directional nighttime traffic schedules are reflected and pilot and tugboats services scheduled in the traffic flow direction, visibility, current and storm information are also integrated into the model. The effects of factors such as pursuit distance, vessel profile, pilot availability, arrival rate and visibility over selected performance measures are investigated through scenario analysis and the most important factors are determined as arrival rate of vessels and visibility.

Keywords: Strait of Istanbul, Maritime traffic, Simulation

1. INTRODUCTION
The Istanbul Strait, 31 kilometers in length is one of the narrowest waterways in the world with only 660 meters at its narrowest point (Almaz 2006). Vessels navigating through the Strait have to make many sharp turns (between 45 and even 80 degrees) which carry high risks for the vessels in such a narrow channel (Ulusçu et Al. 2009). The Strait which is situated in the middle of a huge metropolitan area of 15 million residents, features a very heavy maritime traffic (more than 51,000 vessels annually), with more than 15,000 such vessels carrying dangerous cargo; there is also heavy local traffic including more than 2,000 passenger ferry trips daily between the two shores (Gönültaş 2007).

One noteworthy property of the Strait is the prevailing currents which may rise up to 8 knots speed. Other adverse meteorological conditions like fog, wind, rain and storm also increase the difficulty of navigation in the Strait. In dense fog conditions, vessel traffic may be partially or wholly suspended until meteorological conditions improve, which causes dangerous and unwanted pile-ups at the Strait entrances and puts further strains on the maritime traffic management, since it increases navigation problems (Özbaş 2005).

The Vessel Traffic System (VTS) was established in 2004 in order to regulate and guide maritime traffic in the Strait, in accordance with international and national conventions and regulations, while improving safe navigation, protecting life and environment. Within the framework of this system, vessels desiring to transit the Strait have to submit two reports to the VTS, Sailing Plan 1 (SP-1) and Sailing Plan 2 (SP-2). SP-1 includes all the information about the vessel and must be submitted at least 24 hours before the arrival. SP-2 is of vital importance for planning of vessel passages from the Strait and must be submitted at least 2 hours or 20 nautical miles (whichever comes first) prior to entry into the Strait. The VTS analyze the data in these reports and prepare a safe daily sailing traffic plan (VTS Users' Guide).

2. SIMULATION MODEL
The first step to better understand the risks generated by the maritime traffic in the Strait is to understand and model the maritime actively in the Strait. This study aims to design and develop a simulation model to represent the actual traffic flow in the Strait with regard to the VTS rules and regulations (R&R) and policies that meteorological and geographical conditions, support services (like pilot and tugboats) and frequency, type and cargo characteristics of vessel arrivals (to make a passage through the Strait) with the aim of identifying the impact of such factors on traffic conditions, potential problems and bottlenecks for a less risky transit and overtaking allowance during the passage of vessels on Strait lanes.

2.1. Vessel Classification
The VTS has a specific vessel classification system based on vessel types, cargo characteristics and vessel lengths. In this study a somewhat simplified version of this classification (which is displayed in Figure 1) is used.

The main reason why tankers and dangerous cargo vessels up to 100 meters and LPG-LNG up to 150 meters, tankers and dangerous cargo vessels between 100 and 150 meters and dry cargo carrying vessels between 150 and 300 meters are placed in the same class is that according to the VTS regulations, they have to satisfy the same conditions in entering and navigating the Strait. This way of classification simplifies the understanding of vessel entrance and sailing conditions.

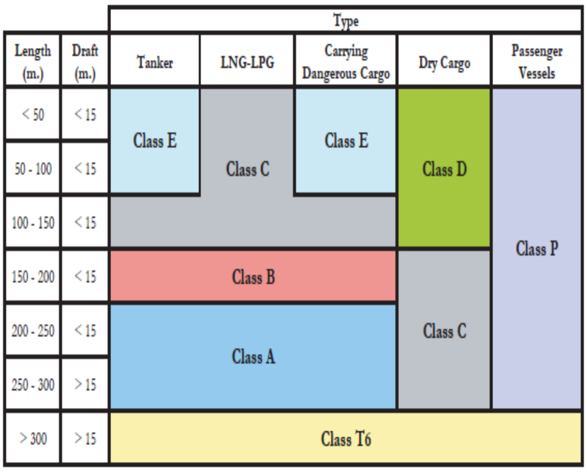

Figure 1: Vessel Classification

2.2. The Arrival Process

The Arena Input Analyzer which is a very efficient tool for distribution fitting to data is deployed in fitting interarrival time distributions. Via the Input Analyzer's Fit menu, all probable distributions fitted to the actual data are revealed and "fit all" property estimates the distribution with the minimum square error. After fitting a distribution, a histogram and the probability density function (pdf) superimposed on the histogram summarize the characteristics of the fit (Law and Kelton 2007). To illustrate, the best fitted interarrival time distribution of northbound Class E vessels is found as the Gamma distribution with shape parameter α being 648 and scale parameter β being 0.974. In the summary report of Arena Input Analyzer (as displayed in Figure 2), the shape of the probability density function overlaps with the histogram and just looking at this figure, one gets the feeling that the selected function represents the actual interarrival time data quite well.

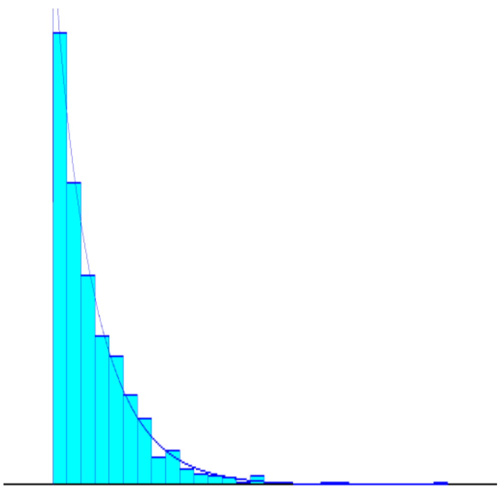

Figure 1: Histogram of northbound Class E interarrivals

2.3. The Istanbul Strait Traffic Rules and Regulations

Vessels enter the Strait either from the north, (traveling south and thus are called as southbound vessels) or from the south (traveling north and thus are called northbound vessels) entrances.

Some R&R related to vessel transit management that are also reflected in the simulation model are as follows:

- There should be at least a 10-minute interval between two consecutive ready to enter vessels from one direction.
- Class A and T6 vessels pass through the Strait only during daytime.
- No vessels are allowed to meet with Class A vessels.
- Class B, C and E vessels should not meet each other during bi-directional nighttime flow.
- There should be at least 75 minutes between two consecutive southbound Class A vessels and at least 90 minutes between two consecutive northbound Class A vessels.
- Passenger vessels are allowed to the Strait regardless of their direction of flow when pursuit distance, meteorological and pilot and tugboat request conditions are satisfied.
- Southbound stopover vessels have priority over northbound stopover vessels, which have priority over any non-stopover vessels.

2.4. Vessel Sequencing

Observations of the 2009 transit data and discussions with the VTS authorities have indicated that the implementation of the regulations regarding pursuit distances between two consecutive vessels of various classes can be parameterized into a set of easily followed rules.

Let θ be the minimum pursuit distance between two consecutive vessels of class D, E, P traveling northbound and let μ be the minimum pursuit distance between two consecutive vessels of class D, E, P traveling southbound. According to the R&R, the minimum pursuit distance between a northbound (southbound) class D, E or P vessel and a class A, B or C vessel sailing in the same direction is also θ (μ). The minimum pursuit distance between two consecutive class C vessels traveling northbound (southbound) is $2*\theta$ ($2*\mu$) and the minimum pursuit distance between a northbound (southbound) class C and a class A or B vessel sailing in the same direction is also $2*\theta$ ($2*\mu$). The minimum pursuit distance between two consecutive A and B vessels traveling northbound (southbound) is respectively $6*\theta$ ($6*\mu$) and $4*\theta$ ($4*\mu$).

2.5. Daytime Vessel Scheduling

As mentioned before, traffic flows from one direction at a time during daytime. The maximum duration of daytime and start time of the daytime traffic differ according to seasons. The first direction of vessel flow into the Strait at daytime is determined based on the total number of vessels in queues and their waiting time regarding vessel priorities (two hours before the starting time). The formula used for in the determination of starting direction is as follows:

$$S^d = a * \frac{Ca*NQ(A)^{(d)} + Cc*NQ(C)^{(d)} + Cd*NQ(D)^{(d)} + Ce*NQ(E)^{(d)}}{NQ(A)^{(d+d')} + NQ(C)^{(d+d')} + NQ(D)^{(d+d')} + NQ(E)^{(d+d')}}$$

$$+ b * \frac{Ca*WT(A)^{(d)} + Cc*WT(C)^{(d)} + Cd*WT(D)^{(d)} + Ce*WT(E)^{(d)}}{WT(A)^{(d+d')} + WT(C)^{(d+d')} + WT(D)^{(d+d')} + WT(E)^{(d+d')}} \quad (1)$$

where:
S^d: score value of the active direction d
$S^{d'}$: score value in the opposite (passive) direction d'
α: multiplicative constant for number of vessels in queues
b : multiplicative constant for waiting time of vessels in queues
Ca: coefficient for A type vessels
Cc: coefficient for C type vessels
Cd: coefficient for D type vessels
Ce: coefficient for E type vessels
$NQ(i)_{t_s}^{(d)}$: number of i type vessels in queue in active direction d at time $t=t_s$
$NQ(i)_{t_s}^{(d')}$: number of i type vessels in queue in passive direction d' at time $t=t_s$
$WT(j)_{t_s}^{(d)}$: total waiting time of j type vessels in active direction d at time $t=t_s$
$WT(j)_{t_s}^{(d')}$: total waiting time of j type vessels in passive direction d' at time $t=t_s$

This formula is applied for both directions and the direction with higher score is declared as the starting direction of the daytime traffic schedule. Two significant factors influencing the determination of the first direction of daytime flow are the number of vessels in queues and vessel waiting times and they are in different level of significance. (The associated weights α and b are nominated as 0.25 and 0.75 respectively).

Class A and T6 vessels are the most critical vessels in terms of the risks they generate. Therefore, in order to set out the framework for daytime schedule, (after attaining the first direction of daytime traffic), number of Class A vessels transiting from both directions are estimated. In this respect, maximum daytime duration is divided into two, proportion to the number of Class A vessels in northbound and southbound queues.

Starting direction traffic time window length is calculated as:

$$W_d = \frac{NQ(A)_{t_s}^{d}}{NQ(A)_{t_s}^{d} + NQ(A)_{t_s}^{d'}} \quad (2)$$

Opposite direction traffic time window length is calculated as:

$$W_{d'} = \frac{NQ(A)_{t_s}^{d'}}{NQ(A)_{t_s}^{d} + NQ(A)_{t_s}^{d'}} \quad (3)$$

The number of Class A vessels planned to enter the Strait during the starting direction vessel traffic flow is:

$$N_p(d) = \frac{W_d}{6*\delta(d)} \quad (4)$$

where:

$$\delta(d) = \begin{cases} \theta & \text{if } d \text{ is northbound} \\ \mu & \text{if } d \text{ is southbound} \end{cases} \quad (5)$$

The parameters in the denominator changes with regard to starting direction decision.

The number of Class A vessels planned to enter the Strait during the opposite direction vessel traffic flow is:

$$N_p(d') = \frac{W_{d'}}{6*\delta(d')} \quad (6)$$

Both $N_p(d)$ and $N_p(d')$ are rounded down to nearest integer numbers.

Waiting time of vessels is adjusted depending on whether they are stopover vessels or not. The adjusted waiting time of vessel j is defined by:

$$W_j^a = c*WT_{t_s}^d(j) \quad (7)$$

where:

$$c = \begin{cases} 1.5 & \text{if } j \text{ is a stopover southbound vessel} \\ 1.25 & \text{if } j \text{ is a stopover northbound vessel} \\ 1 & \text{otherwise} \end{cases} \quad (8)$$

Since passenger vessels have the highest priority in vessel sequencing, the model first searches the Class P queue in the determined direction. If there exist any P vessels in the determined direction and if the visibility conditions and pilot and tugboat demand are satisfied, the one having the maximum elapsed waiting time is allowed to the Strait and the time is incremented as θ (μ) minutes. Meanwhile, if there exist any P vessels on the other side, the one with the maximum elapsed waiting time is allowed to the Strait as well (even though a uni-directional time window is in action). If there is no P vessel in the determined direction, the model searches the Class A queue. If there is any A type vessel in the determined direction, then the pursuit distance requirements, meteorological situations and pilot and tugboat availabilities are checked. When all conditions are fulfilled, the class A vessel having the maximum elapsed waiting time enters the Strait, otherwise model examines the Class C, E and D vessel queues respectively and allows the one having maximum elapsed waiting time regarding their minimum pursuit distances among class types. As soon as a vessel enters the Strait, again time is incremented as the minimum pursuit distance interval (as θ or μ minutes) and the other distance rules among vessel types are also checked until the last planned A vessel in the active direction enters the Strait.

Since the original daily schedule is made in the morning (two hours before traffic start time), the uni-directional time windows of that schedule are designated to service just the available vessels (especially A vessels) at that time. So, close to the end of the time window of the starting direction, say at time t=$\bar{t}$, the model reviews the number of Class A vessels in queues and revises the original schedule to extend the uni-directional time windows as long as the maximum daytime duration permits. This extended time interval is named as the slack time.

For slack time traffic plan, the number of Class A vessels planned to enter the Strait during the starting and opposite direction uni-directional traffic flow time windows is computed by dividing this apportioned times by the minimum pursuit distance between two consecutive Class A vessel transiting from starting and opposite directions time windows.

The length of slack time is:

$$ST = MAX(0, DT - (\bar{t} - t_s + W_{d'})) \tag{8}$$

where t_s is the start time of the first direction vessel traffic flow.

The steps for slack time schedule at time t=$\bar{t}$ are as follows:

(i) Number of Class A vessels in the opposite direction at time t=$\bar{t}$ is checked. One important detail at this point is ignoring the number of previously planned vessels in the opposite direction (N_p (d')), since they are already scheduled to pass in the original time window determined at plan time. Namely, the new arrivals (since plan time) of class A vessels in opposite direction are:

$$NQ_{\bar{t}}(A)^{d'}_{SLACK} = MAX(0, (NQ(A)^{d'}_{\bar{t}} - N_p(d'))) \tag{9}$$

(ii) The additional waiting time of new arrival (since plan time) class A vessels in direction d' at time $\bar{t}$ is computed. This can be done by removing the realized waiting time of planned A vessels from total waiting time of Class A in direction *d'*, that is:

$$WT(A)^{d'}_{SLACK} = WT(A)^{(d')} - WT(A)^{d'}_{t_s} \tag{10}$$

(iii) The ratio for number of unscheduled class A vessels in both directions is estimated as:

$$X = \frac{NQ(A)^{(d)}}{NQ(A)^{d'}_{SLACK}} \tag{11}$$

Since $\bar{t}$ represents a time point at which all scheduled vessels in the active direction have already moved into the Strait, the numerator must only contain the new arrival class A vessels since plan time.

i) The ratio for waiting time of unscheduled vessels in direction *d* and *d'* at time $\bar{t}$ is calculated as:

$$Y = \frac{WT(A)^{(d)}}{WT(A)^{d'}_{SLACK}} \tag{12}$$

ii) If the amount of slack time is larger than or equal to time length that allows a southbound A vessel transit (6*μ), the slack time algorithm tries to make use of this time by scheduling one more northbound or southbound class A vessel.

iii) The indicator Z is determined as follows:

$$Z = X * \alpha + Y * b \tag{13}$$

iv) The exact procedure of allocating the slack time to additional northbound and / or southbound class A vessels is as follows:

a. If Z is greater than or equal to 1, it is deduced that the additional class A vessel (planned to pass in the slack time) should be a *d*-directional vessel and then the equations (11) and (12) are updated. Number of *d*-directional planned A vessels in slack time ($N(d)^{SLACK}_p$) is incremented by one.

$$N(d)^{SLACK}_p = N(d)^{SLACK}_p + 1 \tag{14}$$

and the slack time length is updated as:

$$ST = ST - 6 * \delta(d) \tag{15}$$

b. If Z is less than 1, it is deduced that the additional class A vessel (planned to pass in the slack time) should be a *d'*-directional vessel and then the equations (13) and (14) are updated. Number of *d'*-directional planned A vessels in slack time ($N(d')^{SLACK}_p$) is incremented by one and the slack time length is updated same as equation (15).

$$N(d')_p^{SLACK} = N(d')_p^{SLACK} + 1 \qquad (16)$$

(viii) Returning to step (iii), the algorithm proceeds until the end of ST.

By means of this reschedule procedure, more vessels from both directions are scheduled and admitted to transit until the end of the slack time.

At the end of the (extended) starting direction time window (i.e. with the entrance to the Strait of the last scheduled class A vessel from that direction), the traffic is closed from both directions until the last vessel leaves the Strait. Since it takes approximately 30 minutes for a class A at Filburnu (in northbound traffic flow case) or at Boğaziçi Bridge (in southbound traffic case) to completely exit the Strait, the time gap between the last northbound or southbound Class A vessel and the following vessel from the opposite direction should be 6* θ+ 30 or 6* μ+30 minutes, respectively.

At the end of the starting direction time window (i.e. with the entrance to the Strait of the last scheduled class A vessel from that direction), the traffic is closed from both directions until the last vessel leaves the Strait. The start and execution of the vessel traffic flow in the opposite direction traffic is the same as the first direction flow. Vessels are allowed into the Strait until reaching the number of planned A vessels in this direction. If slack time admits any more A vessels in this direction, they also enter the Strait until the start of the nighttime vessel traffic. A typical example for daytime vessel schedule is displayed in Figure 3.

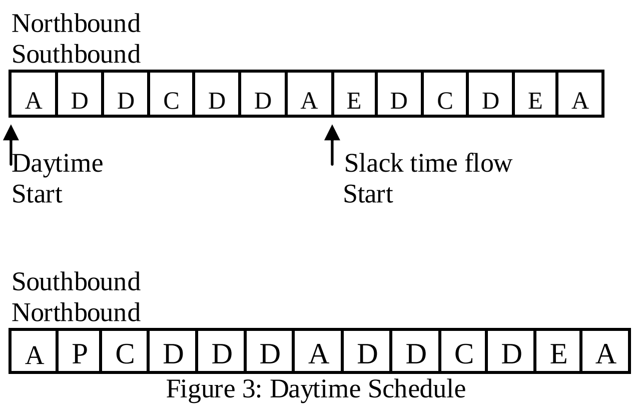

Figure 3: Daytime Schedule

2.6. Nighttime Vessel Scheduling

When daytime traffic ends, the active traffic flow direction remains as the first (active) direction of nighttime traffic. Additionally, unlike daytime uni-directional traffic, at nighttime, there exist two restricted vessel flows (according to the R&R, Class D vessels may enter from the opposite direction when there are such vessels available and meteorological conditions allow since no Class A vessels are allowed from either direction during nighttime).

Number of Class B vessels and the number of all Class C vessels (the ones which will be used for deciding windows length after sequencing class B vessels) at nighttime plan (t=t_n) are updated in starting and opposite directions respectively as follows:

$$NQ_{t_n}^{d}(B_{up}) = NQ_{t_n}^{d}(B) + MAX(0, (NQ_{t_n}^{d}(C) - (NQ_{t_n}^{d}(B) - 1)) / 2) \qquad (17)$$

$$NQ_{t_n}^{d'}(B_{up}) = NQ_{t_n}^{d'}(B) + MAX(0, (NQ_{t_n}^{d'}(C) - (NQ_{t_n}^{d'}(B) - 1)) / 2)$$

Then, the tentative time window length in the nighttime active direction is calculated as follows:

$$NW_p(d) = NT * \frac{NQ_{t_n}^{d}(B_{up})}{NQ_{t_n}^{d}(B_{up}) + NQ_{t_n}^{d'}(B_{up})} \qquad (18)$$

The tentative time window length in the nighttime passive direction is calculated as follows:

$$NW_p(d') = NT * \frac{NQ_{t_n}^{d'}(B_{up})}{NQ_{t_n}^{d}(B_{up}) + NQ_{t_n}^{d'}(B_{up})} \qquad (19)$$

where *NT* is the total nighttime duration, which is the time gap between the following day's daytime traffic plan start time and the end of the present day's daytime windows.

Accordingly, the number of Class B vessels planned to enter the Strait in the active direction flow is:

$$N_p^B(d) = \min(NQ_{t_n}^{d}(B), \frac{NW_p(d)}{4 * \delta(d)}) \qquad (20)$$

The number of Class B vessels planned to enter the Strait in the passive direction flow is:

$$N_p^B(d') = \min(NQ_{t_n}^{d'}(B), \frac{NW_p(d')}{4 * \delta(d')}) \qquad (21)$$

Presuming Class B the most critical group in the nighttime schedule, the length of the northbound and the southbound time windows are outlined by Class B vessels (similar to the role of Class A vessels in daytime scheduling). However, the relatively high population of the abundance of Class C vessels (around 9000 Class C vessels in a year) necessitates the consideration of this class while designing the nighttime traffic plan. Considering that minimum pursuit distance between two Class B vessels is 4*θ (4*μ) whereas minimum pursuit distance between a Class B vessel and a Class C vessel is 2*θ (2*μ), the duration of nighttime restricted traffic flow time is determined by the number of planned Class B vessels (multiplied by 2*θ or 2*μ, according to the active direction), and the number of remaining class C vessels (multiplied by θ or μ, according to the active direction).

The total number of Class C vessels planned to enter the Strait after sequencing class B vessels in the active direction flow is:

$$N_p^{(C)}(d) = \max\left(0, \frac{NQ_{t_n}^{d}(C) - (N_p^B(d) - 1)}{2}\right) \qquad (22)$$

The total number of Class C vessels planned to enter the Strait after sequencing class B vessels in the passive direction flow is:

$$N_p^{(C)}(d') = \max\left(0, \frac{NQ_{t_n}^{d'}(C) - (N_p^B(d') - 1)}{2}\right) \qquad (23)$$

Both equations (22) and (23) are rounded down to nearest integer numbers.

The resulting total nighttime vessel traffic duration in the active direction is:

$$NW(d) = \min(NW_p(d), N_p^B(d)*4*\delta(d) + N_p^C(d)*4*\delta(d)) \qquad (24)$$

The resulting total nighttime southbound vessel traffic duration in the passive direction is:

$$NW(d') = \min(NW_p(d'), N_p^B(d')*4*\delta(d') + N_p^C(d')*4*\delta(d')) \qquad (25)$$

Once the scheduled transit of Class B and C vessels is completed, if there is remaining nighttime, Class D and E vessels continue entering the Strait from both directions (with Class E still having higher priority) according to the minimum pursuit distances (θ or μ) rules.

2.7. The Traffic Lanes and Overtaking

In the model, vessels follow two main lanes, (the northbound or the southbound lanes) and the overtaking lane, if permitted, while transiting the Strait. The whole Strait is divided into 22 slices with stations. Slices are at eight cables (0.8 nautical miles ≈ 1.482 km.) intervals and in order to sustain a predetermined pursuit distance between vessels each slice is also composed of 2 cables long substations. Since stopping in the Strait for any reason is not allowed, vessels continuously move from one station to another during their stay in the Strait. Overtaking is allowed in the Strait except at the narrowest part, according to these conditions:

- When a vessel is in the overtaking lane, there should be no other vessel in this lane in the opposite direction at least up to the next station.
- There should be at least the pursuit distance between two closest vessel in the overtaking lane traveling the same direction.
- After overtaking is completed, vessels move back to the main lanes.

2.8. Pilot and Tugboat Services

According to the R&R, having a pilot captain on board during the Strait passage is compulsory for vessels longer than 250 meters and optional (though strongly recommended) for other vessels. All vessels express their pilot captain and tugboat needs in their SP-1 and SP-2 reports. There are 20 pilots and 6 tugboats available(as in the real situation).

In the simulation model pilots and tugboats are treated as resources which are seized by vessels at the embarking area in the Strait and released while leaving. In order to meet pilot and tugboat needs, every hour the model searches the number of available pilots (including transferring pilots) in the active direction and requests pilots from the opposite side when it is less than 6. The model also searches the number of available tugboats in the active direction and requests tugboats from the opposite side when it is less than 3. During the nighttime time windows, number of pilots at both sides is equalized to 6 and tugboats to 3 to meet the pilot and tugboat demand. Once a piloted vessel's passage in a certain direction is completed, the pilot is released from its current duty and included in the set of available resources for the opposite direction.

2.9. Visibility Conditions

According to the R&R, when visibility is less than one nautical mile in the Strait (called FogType1, only one-way traffic is permitted and when visibility in the Strait is less than 0.5 mile (called as FogType2), vessel traffic is suspended in both directions. The visibility module in the simulation model reads the fog information from the visibility data of (Almaz 2006) externally. Before a vessel is allowed to enter the Strait from the active direction during daytime, visibility condition is checked; if there is a FogType2 event, the vessel waits until it disappears. FogType1 does not affect daytime flows very much (since almost all vessel activity with the exception of class P vessels is uni-directional anyway); only the class P vessels coming from the opposite (passive) direction are stopped. When a FogType1 occurs at nighttime, however, two-way traffic is suspended.

2.10. Current Conditions

The most dominant current type on the Strait is the southbound surface current caused by level difference between the Black Sea and the Mediterranean Sea. The current module of the simulation model is integrated into the model from the previous study (Almaz 2006). In the study, the most effective southbound current is taken into account and a moving average function is built to estimate a daily base current value. Then, the current level at different regions of the Strait are assigned as predetermined percentages of the base value, based on historical current data. In order to comply with the R&R, when current speed exceeds 4 knots, class A, B, C and E vessels having a speed less than 10 knots are not allowed into the Strait. Moreover, all vessels in these classes have to wait in their queues (until current conditions stabilize) when current speed exceeds 6 knots.

3. OUTPUTS OF THE MODEL

This model is run for the 13 months time period (between 1 December 2008 and 1 January 2010). The first month is considered as the warm up period. Some performance measures determined for the analysis are:

- R1:The average waiting time of vessels (aggregate and vessel type based);
- R2:Total number of vessels passed;
- R3:Average number of vessels in queues;
- R4:The entire Strait vessel density;
- R5: Pilot utilization;

4. VERIFICATION AND VALIDATION

Due to the fact that the simulation model in this study consists of many submodels integrated into the main traffic model running concurrently, it is difficult to monitor the system. However; with the trace module of Arena, arrival of each vessel, attributes assigned to it, its movement to the anchorage area or to the appropriate queues and its admittance to the Strait are followed clearly, while simultaneously watching entities related to meteorological events affecting the system. Moreover, animation reveals all events in the whole system; therefore, logic errors can be captured easily. Variable indicator of the Arena is also a frequently utilized tool in this study. The change in values of performance measures can directly be traced by variable indicators.

Extreme condition verification is first performed by increasing vessels arrival rates by 20% in a three month simulation run. When compared to the base scenario, average vessel waiting time shows more than fifteen-fold increase (from 541 minutes to 9272 minutes), average number of vessels in queues increase from 52.6 to 1154.4, number of vessels passed increases to 14756 from 12845 and pilot utilization increases from 0.23 to 0.25.

Another extreme conditions effect is reducing the total number of pilots in the model to 12 instead of 20. The model is run for one year with 25 replications and as expected, the pilot utilization, average, maximum waiting time of vessels and number of vessels in queues increased and total number of vessels passed the Strait decreased.

The most conclusive of the validation tests in this study are the output comparisons with the real 2009 data. The results of selected performance measures are sufficiently close to the data 2009 to support the claim that the model mimics the actual system reasonably well. As an example, average waiting times of all vessels in model and in actual data are compared. The results are quite similar to each other, as displayed in Table 2.

Table 2: Comparison of average waiting time of vessels

Waiting Times (in minutes)				
	2009 Data	The Simulation Model		Relative Error (%)
		Average	Half Width	
All Vessels	842	814.4	123.13	-3.28

5. SCENARIO ANALYSIS AND RESULTS

Four factors are selected for the scenario analysis of the simulation model:

- A: minimum pursuit distance (in time units) between vessels
- B: vessel profile
- C: pilot policy
- D: arrival rate

The levels of identified factors for scenario analysis are displayed in Table 3.

Table 3: Main factors and their levels in scenario design

Factor	Name	Low	Average	High
A	pursuit distance	13N-11.5S	13.5N-12S	14N-12.5S
B	vessel profile	base	base	>=150 m
C	Pilot availability	16	20	24
D	arrival rate	base	5% more	10% more

The first factor A with three levels is the minimum pursuit interval between two consecutive vessels (13N for the low setting means 13 minutes interval for northbound vessels and 11.5S means 11.5 minutes interval for southbound vessels). Regarding the vessel profile factor B, the low setting corresponds to the base scenario in which vessels demand pilots according to the pilot request frequency distribution of vessel classes generated based on the 2009 data. In the high setting, in addition to this random pilot demand, all vessels longer than 150 meters are routinely assigned a pilot while passing the Strait. In pilot availability factor C, the number of available pilots is set at 16 for the low level and 20 for the average level (as is the case in the current system) and 24 for the highest level. According to the last factor, regarding the arrival rate of vessels D, the low setting (which is the setting assumed in the base scenario) is taken as the rates estimated in the interarrival distribution for each subclass based on the 2009 data. In the average level, arrival rate of vessels is increased by 5 per cent (compared to the rates estimated based on the 2009 data) and in the high level, vessel arrival rates are increased by 10 per cent.

Accordingly, a total of 54 different scenarios (including the base scenario), are projected and run with 25 replications for a full factorial design. The outputs of these scenarios are gathered from Arena reports, the significant factors and their interactions are investigated through the ANOVA tables in the Design Expert 8.0 software. The percent contribution of each factor on performance measures are displayed in Table 4.

Table 4: Percent contributions of main factors

	A	B	C	D	AD
Average waiting time	38			59	2.4
Total vessels passed	0.3	0.1	0.1	98	0.1
Average transit time				89	
Pilot utilization	0.3	3.1	93	3.5	
Vessel density	0.3	0.1	0.1	99	0.1

In order to track the effects of factors easily, single factor level change in scenarios is investigated through the comparison of scenarios 19, 3, 7 and 16 with the base scenario 1 as can be seen in Table 5.

Table 5. Scenarios with various factor level changes

Scenarios	R1	R2	R3	R4	R5
1	814	51,178	79.9	9.45	0.24
19	608	51,206	59.2	9.46	0.24
3	722	51,204	70.3	9.46	0.31
7	754	51,200	73.4	9.45	0.25
4	2289	56,628	251	10.5	0.26
10	2275	56,624	250	10.5	0.27
12	2170	56,677	237	10.5	0.22
25	663	51,193	64.6	9.45	0.25
49	614	53,880	62.8	9.95	0.22
52	622	53,882	63.7	9.95	0.25

Decreasing pursuit distance to 13.5 minutes for south entrances and to 12 minutes for north entrances (scenario 19), primarily decrease the waiting time (by 25 per cent), decrease the number of vessels in queues by 26.25 per cent, while keeping the total number of vessels passed and vessel density almost the same. Decreasing the number of available pilots from 20 to 16 (scenario 3) increases pilot utilization by 29.2 per cent and decreases waiting time by 11.30 per cent (the reason why the average waiting time decreases is due to decrease in waiting time of Class D vessels, which enter the Strait more frequently while other vessel types remain waiting because of pilot unavailability). Assigning pilots for all vessels longer than 150 meters (scenario 7) increases pilot utilization by 4.1 per cent. Increasing vessel arrival rate by ten per cent (scenario 4) increases total number of vessels passed by 10.64 per cent, average waiting time by 181 per cent, number of vessels in queues by 212 per cent, pilot utilization by 29.2 per cent and vessel density by 10.8 per cent. The effect of two, three and four factor level changes over responses is also investigated. For instance, decreasing pursuit distance to 13.5 minutes for northbound and to 12 minutes for southbound vessels while assigning pilot for all vessels longer than 150 meters (scenario 25) decrease the waiting time by 18.6 per cent when compared to the base scenario; however, waiting time is increased by 9.9 per cent when compared to the single factor level change case involving 13.5 minutes pursuit distance for south entrances and 12 minutes for north entrances (scenario 19). Table 5 also displays that increasing vessel arrival rate by ten per cent and 20 available pilots to 24 in the system while assigning pilot for all vessels longer than 150 meters (comparison of scenarios 10 and 12) decrease the waiting time by 4.62 per cent and number of vessels in queues by 5.22 per cent. Furthermore, increasing 20 available pilots to 24 in the system while assigning pilot for all vessels longer than 150 meters under five per cent higher arrival rate (comparison of scenarios 49 and 52) have almost same performance measure results.

In another scenario analysis, 4 factors influencing the response variables under high arrival rate conditions (number of arrived vessels increased by 10 per cent) are analyzed. The levels of factor A are 13.5 minutes for northbound and 12 minutes for southbound in low setting and 14 minutes for northbound and 12.5 minutes for southbound in high setting. Regarding the visibility factor (D), the low setting describes the base scenario in which vessels encounter fog events according to the visibility submodel, whereas in the high setting, the fog pattern of the worst case (i.e. the autumn fog realizations which have the longest fog durations) is chosen as the visibility data for the whole year.

In order to track the effects of factors easily as displayed in Table 6, level change in scenarios is investigated compared to the base scenario 1. Decreasing pursuit distance to 13.5 minutes for north entrances and to 12 minutes for south entrances (scenario 7) primarily decrease the waiting time by 41.5 per cent, decrease the number of vessels in queues by 41.6 per cent, while keeping the total number of vessels passed almost the same. Setting low visibility conditions (scenario 13) increases average waiting time by 88.8 per cent yet does not significantly change the total number of vessels passed. The effect of two and three factor level changes over responses may also be investigated in this table. For example, although reducing pursuit distances to 13.5 minutes for northbound passages and 12 minutes for southbound passages and deploying 24 pilots instead of 20, the average waiting time increases by 82 per cent under low visibility conditions (comparison of scenarios 7 and 20) and number of vessels in queues increase by 91 per cent.

Table 6. Scenarios with various factor level changes under high arrival rate conditions

Scenarios	R1	R2	R3	R4	R5
1	2289	56629	250	10.5	0.3
7	1367	56850	146	10.5	0.3
13	4320	56324	474	10.4	0.3
15	4087	56336	448	10.4	0.4
20	2482	56531	279	10.5	0.2
23	2354	56615	262	10.5	0.2

In the full factorial analysis of the related scenarios, the 24 different scenarios are experimented through 25 replications (i.e. the scenario analysis is composed of 600 distinct observations). In the scenario analysis, the most effective factor on performance measures is observed as visibility conditions. As fog in the Strait becomes stronger, average waiting time of vessels and transit time increase. Moreover, low visibility conditions decrease total number of vessels passed from directions, pilot utilization and vessel density in the Strait.

6. CONCLUSION AND FURTHER RESEARCH

In this study, a simulation model is developed for representing the vessel traffic behavior in the Strait. In this simulation model, maritime rules and regulations about vessel admittance, pursuit distances among vessels, priority levels of distinct vessel types and pilot requirements are all considered. Moreover, submodels representing meteorological conditions such as fog, current and storm are integrated to the model. For validation purposes, the simulation outputs are compared with the actual 2009 data and quite satisfactory results are obtained.

In order to analyze the effects of various factors such as vessel arrival rate, vessel profile, pilot availability and minimum pursuit distances between vessels, on performance measures, 54 scenarios are performed with the full factorial design. The most significant factor for all selected variables is observed as the vessel arrival rate. The minimum pursuit distance between vessels is also significant for most performance measures. The interaction of arrival rate and pursuit distance is effective on the most responses, as well. Pilot availability is principally important for pilot utilization.

Another scenario analysis is conducted when vessel arrival rate is increased by 10 per cent and the visibility factor is added. Results associated with the considered 24 scenarios show that visibility is the most critical factor for performance measures and its interaction with minimum pursuit distance at different levels is also significant for performance measures such as average waiting time of vessels, number of vessels passed and pilot utilization.

This study is planned to be used for risk analysis of the Strait. Incorporating probable vessel accidents and the consequences to the model can have a very beneficial effect for revising the policies and minimizing risk.

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