

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

by

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ABSTRACT

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

The Turkish Straits, the unique water route between the Black Sea and the Mediterranean is of great strategic and economic importance. The increase in the number of transit vessels in recent years and serious quantities of dangerous cargo passing very close to highly populated areas as well as through a very dense local traffic mostly between the European and Asian shores of this narrow waterway are sources of deep concern for Turkey. This study aims to develop an integrated simulation model for the transit maritime traffic in the Strait of Istanbul and to perform scenario analysis to investigate the effects of type and frequency of transit vessels, as well as various natural factors, resources and decision / policy rules, on the system. In this context, the performance measures in concern are the number and types of vessels passed, transit times and waiting times of vessels, number of vessels in the queues, vessel densities throughout the Strait, pilot and tugboat utilizations. Scenario analyses have been designed to investigate the effects of vessel arrival rates, vessel profiles, pilot and tugboat availabilities, current conditions, pursuit distances between vessels, visibility and seasonal conditions on these performance measures. In this regard, the Strait traffic simulation model is equipped with comprehensive arrival process model of transit vessels, a stochastic visibility and a stochastic current model. Current Strait of Istanbul Traffic Rules and Regulations, the available pilotage and tugboat services, traffic lanes and overtaking conditions are all imposed to the model as well. Besides, animation of the model is developed to better describe the structure and to deploy the model as a real time decision support and training tool. Results of the study reveal interesting relationships among factors and responses whereas they point out the importance of external factors of vessel arrivals and vessel profiles and control tools such as pilotage and tugboat supply and pursuit distance in the Strait as well.

ÖZET

İSTANBUL BOĞAZI TRANSİT GEMİ TRAFİĞİNİN BENZETİM MODELLEME VE SENARYO ANALİZİ İLE İNCELENMESİ

Türk Boğazları, Karadeniz ve Akdeniz arasında tek denizyolu olarak büyük stratejik ve ekonomik önemdedir. Son yıllardaki transit gemi sayısındaki artış ve yoğun yerleşim bölgelerine ve bununla birlikte bu dar su yolunun çoğunlukla Avrupa ve Asya kıyıları arasında çalışan yoğun yerel trafiğe çok yakın geçen ciddi miktarda tehlikeli yükler Türkiye için derin bir endişe kaynağıdır. Bu çalışma İstanbul Boğazı'ndaki transit trafik için bütünlük bir benzetim modeli geliştirmeyi ve geçiş talebinin tip ve sıklığının yanısıra çeşitli doğal etkilerin, kaynak ve karar/politika kurallarının sistem üzerindeki etkilerini incelemek için senaryo analizi gerçekleştirmeyi amaçlamaktadır. Bu bağlamda, dikkate alınan başarımlar ölçüleri geçen gemi sayısı ve tipi, gemi geçiş süreleri ve bekleme zamanları, kuyruklardaki gemi sayıları, Boğaz boyunca gemi yoğunlukları, kılavuz kaptan ve römorkör kullanım oranlarıdır. Bu başarımlar ölçülerine gemi geliş oranı, gemi özellikleri, kılavuz kaptan ve römorkör bulunabilirliği, akıntı koşulları, gemiler arası takip mesafesi, görüş mesafesi ve mevsimsel koşullar gibi faktörlerin etkilerini incelemek için senaryo analizleri tasarlanmıştır. Bu bakış ile, Boğaz trafik benzetim modeli ayrıntılı transit gemi geliş süreci modeli, rassal bir görüş mesafesi ve rassal bir akıntı modeli ile donatılmıştır. Güncel İstanbul Boğazı trafik kuralları ve düzenlemeleri, mevcut kılavuz kaptan ve römorkör hizmetleri, trafik şeritleri ve sollama koşulları da modele yüklenmiştir. Ayrıca, yapıyı daha iyi anlatmak ve modeli gerçek zamanlı bir karar destek ve eğitim aracı olarak konumlandırmak için modelin canlandırması geliştirilmiştir. Çalışmanın sonuçları faktörler ve karşılıkları arasındaki ilişkileri açığa çıkarırken gemi gelişleri ve gemi özellikleri gibi dışsal faktörlerin ve kılavuz kaptan ve römorkör sağlanması ve Boğazdaki takip mesafesi gibi kontrol araçlarının da önemine işaret etmektedir.

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LIST OF SYMBOLS / ABBREVIATIONS

ACF	Autocorrelation Function
AR	Autoregressive Process
ANOVA	Analysis of Variance
HazMat	Hazardous Material
KOERI	Kandilli Observatory and Earthquake Research Institute
LNG	Liquid Natural Gas
LPG	Liquid Petroleum Gas
MGE	Mixtures of Generalized Erlang
PACF	Partial Autocorrelation Function
TSS	Traffic Separation Scheme
TSVTS	Turkish Straits Vessel Traffic Services
TUMPA	Turkish Maritime Pilots' Association
WU	Weather Underground Website

1. INTRODUCTION AND STUDY OBJECTIVES

The Turkish Straits, the only water passage between the Black Sea and the Mediterranean, has great strategic and economic importance. Both the Çanakkale and the Istanbul Straits have unique characteristics which bring about complicated navigational conditions. Besides, the volume of traffic flow has already been threatening the safety of navigation in the Straits. In recent years, the increase in the number of transit vessels, transporting large quantities of hazardous material passing right through the center of the densely populated City of Istanbul, and thus carrying major human life, material and environmental risk, has been a source of deep concern for the Turkish State, as well as for the 12 million residents of this huge metropolis. Furthermore, a maritime accident and an ensuing environmental disaster, which would force the closure of the Straits for unpredictable periods, will significantly affect the economies of the Black Sea countries, in addition to the land locked Caucasian and Central Asian States.

The Strait of Istanbul has very special ecological conditions in terms of both marine and terrestrial environment apart from the Strait of Çanakkale. This narrow and winding strait is one of the most hazardous, crowded and difficult waterways to navigate in the world. It also has unique physical, geographical, hydrological and oceanographic characteristics.

The Strait of Istanbul is about 31.7 km long. Its width has a maximum of 4.7 km at the northern entrance and 2.5 km at the southern entrance, while its narrowest part is only 698 meters at the Kandilli – Bebek region (it is known as the narrowest strait in the world). Strait depth varies from 30 to 60 meters and it reaches a maximum of 110 meters at Kandilli (Figure 1.1).

The Strait of Istanbul has 12 sharp turns including a 45 degrees turn at the narrowest region and an 80 degrees turn around Yenikoy. At these turns the rear and forward sights are totally blocked before and during the course alteration. Vessels approaching from the

opposite direction cannot be seen round the bends. Bad weather, fog and unpredictable currents complicate navigation as well.

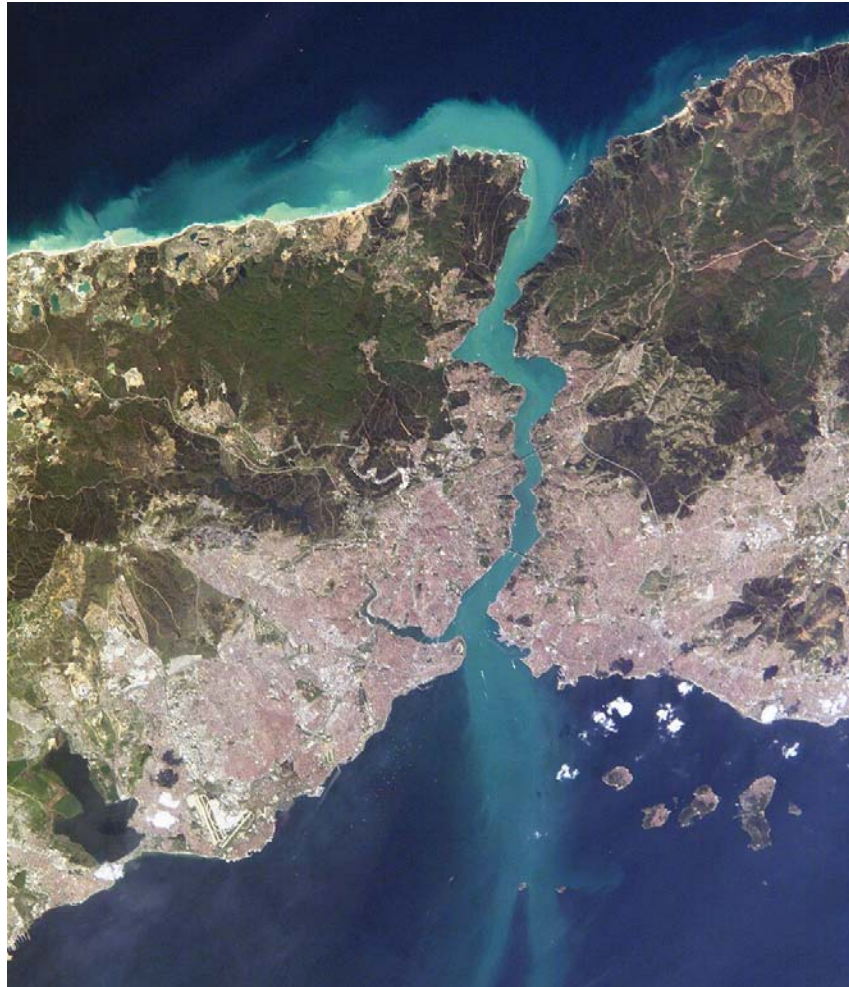


Figure 1.1. Satellite view of the Strait of Istanbul

The most important oceanographic factor affecting the Strait of Istanbul is the current. The density stratification and the sea level difference between the Black Sea and the Sea of Marmara create a two-layer flow system in the Strait. Currents develop under hydrological conditions such as precipitation, evaporation and stream input in the Strait of Istanbul similar to other straits. Geographical structure, the level and the salinity differences between the Black Sea and the Marmara Sea, evaporation and wind affects the current formation as well. There is a southbound surface flow and the northbound lower layer flow which can be observed at a depth of 10 meters in the southern entrance and at a depth of 48 meters in the northern entrance. The speed of the surface current, which is of primary concern for the maritime traffic, may reach up to 6 – 7 knots. Other oceanographic

factors like waves and tides do not affect the maritime traffic in the Strait as much as current and the narrow and twisted nature of the Strait increases the importance of currents. (Örs, 1999; Yüce, 1996).

The Montreux Convention of 1936 regulates the legal regime of the Turkish Straits and this is recognized by the United Nations Convention on Law of the Sea. According to the Montreux Treaty, navigation through the Turkish Straits is unrestricted for commercial vessels, without any differentiation regarding vessel type, vessel flag or the cargo being transported. However, the number of transit vessels passing through the Istanbul Strait was about 4.500 annually at the time the Montreux Treaty was signed, whereas it has been more than 55.000 vessels annually in 2005.

In the face of the serious and increasing risks brought about by the maritime traffic in the Turkish Straits, in 1994 the Turkish State has developed and put into effect a comprehensive set of Rules and Regulations to govern all civilian maritime traffic in the Straits, in order to ensure safe navigation. The new regulations and the Traffic Separation Schemes were approved by the International Maritime Organization (IMO). Then the Turkish Straits Vessel Traffic Services (TSVTS) was established in 2004, in accordance with applicable national laws and international Rules and Regulations, in order to better manage and control the flow of maritime traffic and to improve the safety of navigation. The ultimate goal is protection of life, environment, and property in the Turkish Straits by using the latest technology. Vessels carrying dangerous cargo and vessels 20 meters in length or over, whether in stopover or non-stopover passage through the Turkish Straits, for whatever purpose, are designated as “Active Participant” vessels within the TSVTS area and it is strongly recommended that “Active Participant” vessels comply with all the requirements of the Turkish Straits Reporting System (VTS user’s guide, 2004).

1.1. Vessel Traffic in the Strait of Istanbul

The number of vessels passing through the Strait of Istanbul between 1995 and 2005 is given in Table 1.1 and in Figure 1.2 About 17 per cent increase in total number of vessels passed and 116 per cent increase in the number of tankers passed, signifies the

gravity of the increasing trend in the transit vessel demand and changes in the vessel profile as well.

The increase in the number of transit vessels causes an increase in the pilot demand as well. While deployment of pilot captains ensures safer navigation in the Strait, this increase in the pilot demand may necessitate an increase in the pilot supply in the near future and aggravates possible bottlenecks in the provision of pilotage services.

Table 1.1. Number of vessel transits in the Strait of Istanbul between 1995 and 2005
(Sources: TSVTS; TUMPA)

Year	Total	Used Pilot	Longer than 200 meters	Direct Passed	Tankers
1995	46954	17772	6491	24325	N/A
1996	49952	20317	7236	23755	4248
1997	50942	19752	6487	24568	4303
1998	49304	18881	1943	24561	5142
1999	47906	18424	2168	26323	4452
2000	48079	19209	2203	26858	4937
2001	42637	17767	2453	26113	6516
2002	47283	19905	3113	29398	7427
2003	46939	21175	2923	28961	6578
2004	54564	22318	N/A	34256	N/A
2005	54790	24651	3503	34072	9190

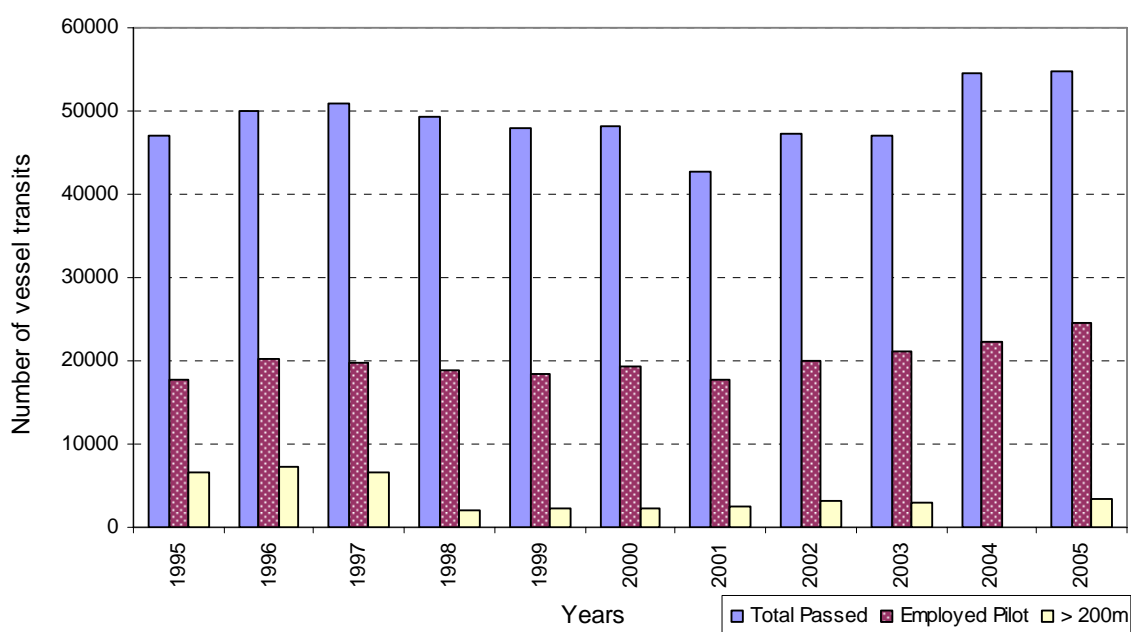


Figure 1.2. Number of total vessels passed, vessels employing pilot and vessels longer than 200 meters between 1995 and 2005 (Sources: TSVTS; TUMPA)

Frequency distribution of all transit vessel types and lengths passed in 2005 is given in Figure 1.3 and in Figure 1.4 respectively. Vessel characteristics are another important issue since the Strait Rules and Regulations may change severely for different vessel characteristics. Therefore, any change in the vessel arrival profile may affect most of the performance measures in the Strait.

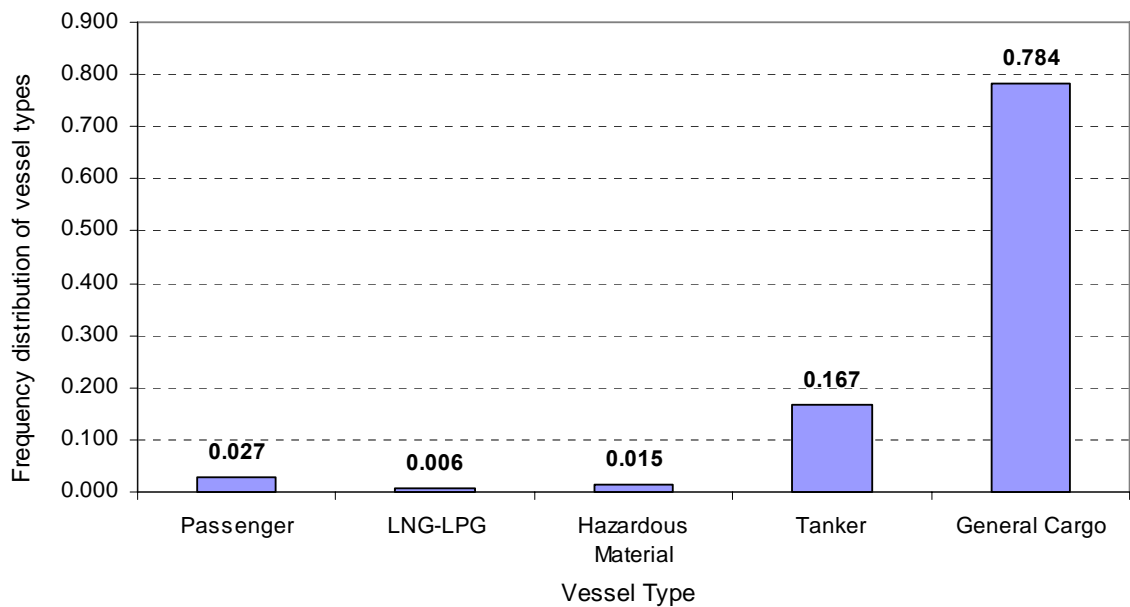


Figure 1.3. Frequency distribution of transit vessel types in 2005 (Source: TSVTS)

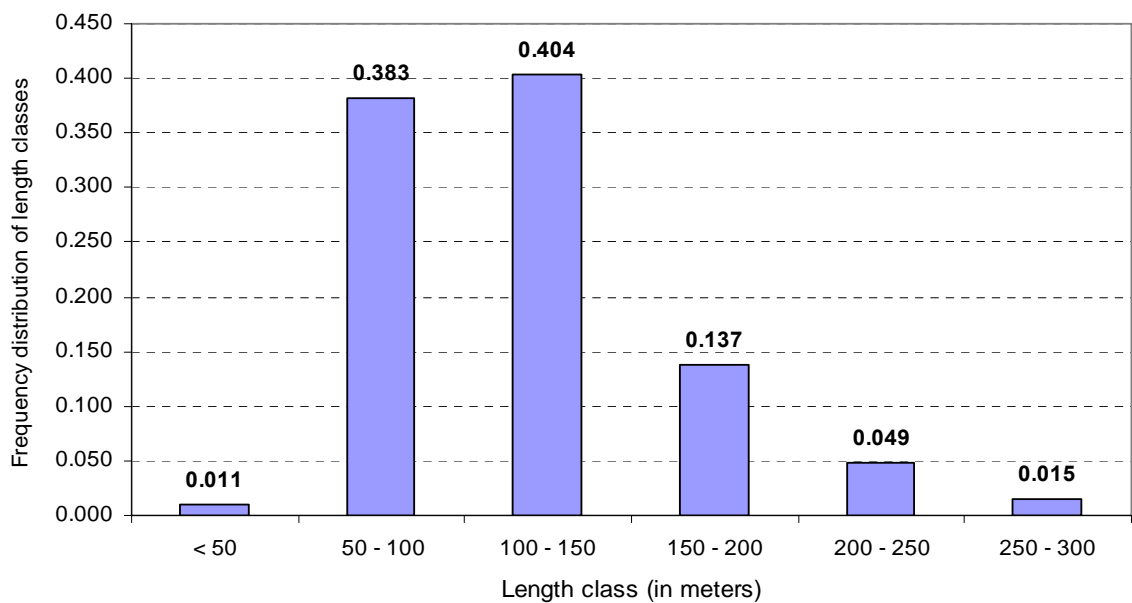


Figure 1.4. Frequency distribution of transit vessel lengths in 2005 (Source: TSVTS)

Seasonal variation in the number of vessel transits is given in Figure 1.5. Seasonality of the vessel traffic in the Strait has different aspects. Daytime length and visibility conditions in different seasons affect the number of vessels passed. Figure 1.5 especially highlights the fact that, on the overall, the vessel transits in winter seasons are less than the vessel transits in summer seasons.

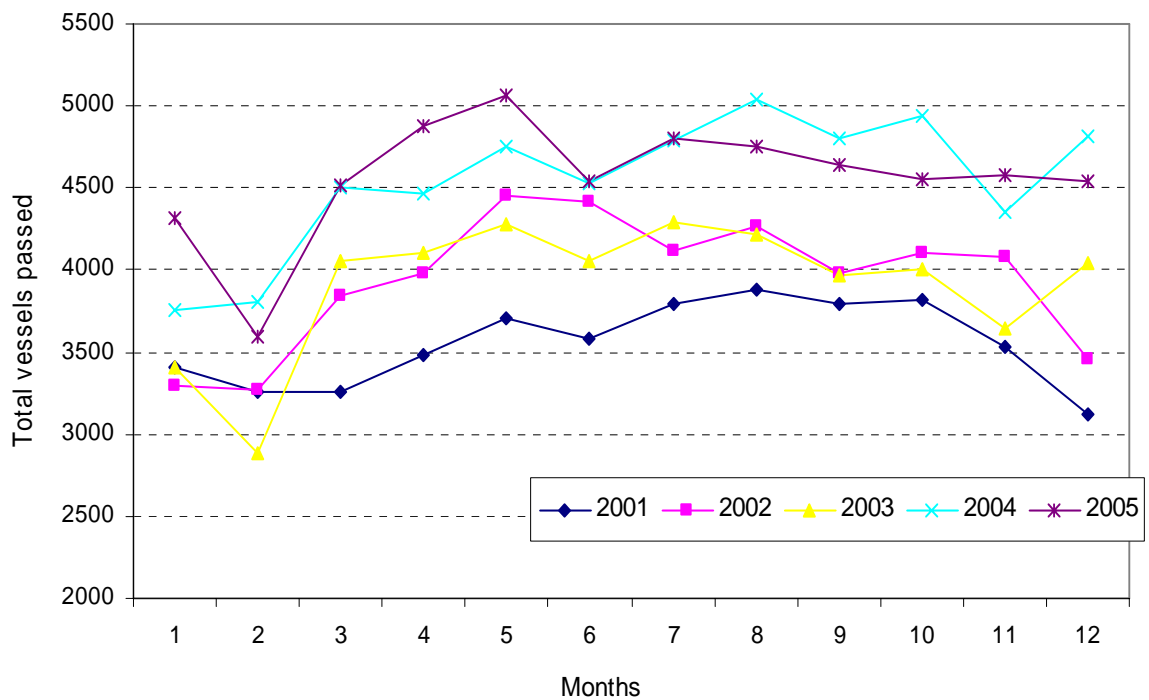


Figure 1.5. Monthly distribution of number of vessels passed between 2001 and 2005
(Sources: TSVTS; TUMPA)

All these different factors and policies affect the transit traffic in the Strait of Istanbul. Especially, the arrival pattern of vessels, natural conditions of current and visibility in the Strait (including the seasonal effects) must be thoroughly analyzed and the Strait Rules and Regulations, support services and the traffic flow in the Strait should be taken into consideration as well. Consequently, interaction of these factors, effectiveness of decisions / policies and relations of these factors and policies with various performance measures has to be investigated in the light of increasing transit demand in the Strait of Istanbul.

1.2. Objectives of the Study

The objective of the study is to develop a functional simulation model of the transit vessel traffic flow in the Strait of Istanbul, which will facilitate the development and analysis of various scenarios regarding environmental and meteorological conditions, type and frequency of transit traffic demand, availability of support services and interpretation of the Strait transit Rules and Regulations. This model is to give due emphasis to realistic representation of the random vessel arrivals, current and visibility realizations, lane structure and flow of transit traffic, as well as to the many detailed rules governing the entrance and flow of transit vessels at the Strait of Istanbul.

This realistic and practical environment will assist to speedily analyze and evaluate the effects of possible transit vessel demand and characteristics, resource availabilities, environmental conditions and policies and will serve as a policy tool for the decision makers governing the maritime traffic in the Strait of Istanbul.

The maritime traffic simulation model developed includes the following major components:

- Stochastic arrival processes of vessels at the north and the south entrance of the Strait based on vessel types and characteristics,
- The Strait Traffic Rules and Regulations,
- The pilotage and tugboat services with predetermined and parameterized capacities,
- A stochastic visibility model for the Strait of Istanbul,
- A stochastic current model for the Strait of Istanbul,
- Transit vessel traffic flow in the Strait of Istanbul.

In line with the study objectives, the simulation model developed involves the conditions affecting the course of transit vessels, and by that means imitates the traffic flow in the Strait.

A better understanding and control of the overall effects of multiple factors is intended through scenario analysis. Via scenario analysis;

- The importance of uncontrollable factors, such as frequency of transit demand and the profile of incoming transit vessels and the effects of control tools available to the Strait Authority against these factors can be revealed,
- Seasonality and the effect of meteorological factors, such as current and visibility, on the traffic flow can be better understood,
- Control tools, such as pilot and tugboat supply, and various interpretations and changes in the application of Traffic Rules and Regulations can be investigated.

From this perspective, scenario analyses are designed to investigate the effects and the interrelations of the factors of vessel arrival rates, vessel profiles, pilot and tugboat availabilities, current conditions, pursuit distances between vessels, visibility and seasonal conditions on the performance measures.

The effects of those factors can be observed on the following performance measures;

- Number of vessels which have completed their transit through the Strait in a given time period,
- Average transit time of vessels passed,
- Average waiting time of vessels (before entering the Strait),
- Maximum waiting time of vessels (before entering the Strait),
- Number of vessels in the queues,
- Vessel density throughout the Strait,
- Pilot utilization,
- Tugboat utilization.

Apart from those factors affecting the transit traffic in the Strait, there are some other factors which have been held beyond the scope of this study. Maritime accident occurrences and local traffic in the Strait of Istanbul have influence on the transit traffic. Meteorological conditions, especially major storms in the Black Sea region also influence

the Strait through affecting vessel arrival patterns and Strait entrance priorities. These situations are not addressed in the model.

This simulation modeling study on the transit maritime traffic in the Strait of Istanbul is conducted under the research project on the comprehensive risk management and analysis of the Strait of Istanbul, with cooperation of Rutgers University and Boğaziçi University through the supports of NSF (National Science Foundation) and TÜBİTAK (Turkish Technological and Scientific Research Institute). The knowledge base and the results of this study is expected to support the further risk management study of the Strait of Istanbul, with the simulation model developed providing the required infrastructure.

1.3. Model Structure

The simulation software Arena 9.0 is used in the development of the simulation model of Transit Maritime Traffic in the Strait of Istanbul. The integrated model comprises of a visibility module, a current module and the main module addressing the southbound and northbound vessel treatments before and during their Strait transit. Additionally, there are some auxiliaries and statistics collection modules in the model.

The simulation model is designed and developed such that all input factors can be randomly generated internally in the model, based on probability distributions obtained from historical data, or the input data can be read from external text files. The reason for this flexibility is that internally generated input data simplify the control of parameters in scenario analysis and allows independent replication runs to analyze the effects of randomness. On the other hand, external reading of real input data facilitate debugging throughout the development process, assists calibration of the model and may enable the deployment of the model as a real time decision support tool for the Strait Traffic Control Authority.

Three classes of control parameters are used in order to clarify the logic of the model and to simplify scenario analysis. These are, external parameters, internal parameters and Traffic Rules and Regulations. External parameters, which cannot be controlled by the Strait Authority, can be summarized as, i) arrival rates, ii) profiles, iii) speeds, iv)

pilot/tugboat demands of transit vessels and meteorological conditions. Pilot and tugboat availabilities, transit vessel priorities and overtaking criteria, pursuit distance between vessels, speed limits in the Strait and Kandilli region encounter prevention rule are the internal parameters of the model, which can be controlled by the Strait Authority. The third class is the Turkish Straits' Maritime Traffic Rules and Regulations, which are regarded as unchangeable throughout this study.

2. LITERATURE SURVEY

In this chapter, previous studies on the Strait of Istanbul and on maritime traffic modeling are presented and discussed. In the literature, there are some risk modeling and accident modeling studies for the Strait of Istanbul. However, there are few works on simulation modeling of maritime traffic in narrow waterways.

The project of SABRE group on the simulation modeling of Panama Canal is presented by Golkar et al. (1998). They developed a functional tool for the Panama Canal Commission to emulate Canal operations under various operating scenarios and to evaluate impact of time delays encountered during transits and the impact of critical supporting resources. Their work comprises of several modules developed in various environments such as database integrations and also a simulation module developed in SIMAN to address different operations.

Or and Kahraman (2002) worked on accident prone conditions in the Strait of Istanbul through Bayesian analysis and simulation modeling. They used Bayesian analysis to obtain estimates for conditional maritime accident probabilities based on the suspected accident causing factors, which can be routinely monitored and recorded over time. In addition, they used simulation modeling to combine the Strait characteristics, the critical traffic rules and behavior in the Strait with the conditional accident probabilities determined through the Bayesian analysis. The observations on the results indicates the effects of transit traffic rate, local traffic density, meteorological conditions and some vessel characteristics on the maritime accidents in the Strait.

Tan and Otay (1999) investigated vessel casualties through a state-space model which represents the waterway and the location of vessels. They built a hydrodynamic model to influence the drift probabilities of vessels and incorporated arrival distributions and other factors in a Markov Chain to derive probabilities of accidents at a given location in a given time. They obtained steady-state distributions and expected number of casualties

to construct various risk charts. The study also asserts that the expected number of casualties is proportional to square of the tanker arrival rate.

Brito (2000) investigated the congestion of traffic in the Strait of Istanbul through an economic and political perspective. He claimed that the congestion of traffic depends on the traffic growth rate and the service rate and thus, worked on the alternative scenarios of these rates and the costs incurred. He also formulated the stability of the traffic and asserted that the number of accidents increases with the square of the flow of traffic. He concluded the discussion suggesting the ration access to the Straits in order to decrease the volume of traffic without reducing the amount of cargo transported.

The maritime accidents in the Strait of Istanbul were studied by Gören (2002) through logistics regression technique and simulation methodology. Accident probability models were generated for different accident categories and integrated to a simulation model to make an assessment of the dynamic nature of risk in the Strait of Istanbul.

Merrick et al. (2003) developed a simulation model to estimate the number of vessel interactions in purpose of investigating the effects of a proposal that was made to increase the frequency and coverage of ferry services in the San Francisco Bay area. Their work allowed evaluation of this increase through adverse conditions such as restricted visibility. Their visibility model is based on dew point and water temperature disparity and calibration constants, which were obtained by either historical data or expert opinion using AHP methodology, to evaluate the required disparity to allow restricted visibility to occur. Their model and analysis was used in the overall assessment of the proposal by the California legislature.

Köse et al. (2003) worked on the simulation of transit maritime traffic in the Strait of Istanbul with AWESIM software and focused on variation of waiting times resulting from different transit vessel arrival frequencies. However, they based their model on the simple assumptions that vessel interarrival times and closure times of the Strait are uniformly distributed. In addition, the Strait Regulations, vessel support services, visibility conditions and current conditions are not specifically modeled.

A research on stochastic prediction of maritime accidents in the Strait of Istanbul is done by Otay and Özkan (2003). They developed a hydrodynamic model of navigation in the Strait, based on some possible motions of vessels affected by surface currents, vessel sizes and pilotage errors and thus, used the model to estimate vessel position distributions along established checklines. The model developed estimates vessel casualties using the geographical characteristics of the Strait to generate risk maps on the expected number of accidents based on location, vessel size and type of casualty.

Franzese et al. (2004) presented the project of Rockwell software to develop a simulation model of the Panama Canal with Arena software. Their model consists of vessel arrivals, traffic rules and vessel sequencing components. The model generates several performance measures such as waiting times, transit times, queue lengths and locks' utilization rates to conduct several experiments with existing and future canal resources.

Yazıcı and Otay (2006) developed a real time control tool for safe navigation route of vessels. Their model simulates possible vessel maneuvers and, through the computation of a probable trajectory tree, the route with minimum casualty risk is predicted, based on the navigational parameters of position, speed and course of vessel.

The study of Özbaş (2005) on the simulation of transit maritime traffic in the Strait of Istanbul is focused on modeling of entrance procedures of the Strait, based on vessel types and lengths, prioritization of vessels for the entry, pilotage and tugboat services and simple vessel transitions throughout the Strait (i.e. pursuit distances, current effects, overtake conditions are not investigated). In this simulation model the vessel entrance rules to the Strait are based on a former application scheme of Strait Rules and Regulations. All vessel arrivals of the model are realized through exponential distributions, in which the parameters and the vessel profile ratios are based on 1999 statistics. Visibility issues are not specifically handled but inputted to the model through external files. The scenario analysis is conducted to evaluate importance of vessel profile, arrival rate, priority of vessels and support services, on the performance measures. Pilot / tugboat availability is found to be the most important factor.

3. DATA COMPILATION AND ANALYSIS

In this chapter, compilation and analysis of the data on arrival of transit vessels to the system, on fog occurrences and resulting closures of the Strait (due to poor visibility) and on current magnitudes and distribution throughout the Strait are presented. Following the analysis of data, model parameters and probability distributions are specified and the primary input processes of the simulation model are developed.

3.1. The Arrival Processes

The arrival processes for transit vessels used in the model are based on the year 2005 vessel arrivals at the Strait of Istanbul. The following are meant by term “arrival process”: the random generation of vessel interarrival times, vessel lengths, speeds, anchoring durations, pilot demands, tugboat demands, and direct¹ or indirect² passing status based on vessel type, vessel length group and entrance direction.

The arrival process initiates with the generation (or the arrival) of a series of individual transit vessels to the Strait entrances. The arrived vessels first enter the anchoring areas according to their request and stay there through their anchoring durations. Those who do not anchor or leave anchoring area are ready to enter the Strait. Queues are designed to hold the already arrived, ready and waiting vessels and to check if the Strait is available and safe for their transit. Waiting times are specifically collected for those vessels that wait in these queues until they enter to the Strait.

There are a total of 53 vessel type codes used in the 2005 data. However; these codes can be classified into 5 general types regarding the application of the Rules. The vessel types considered in the model are i) Passenger Vessels, ii) LNG-LPG Carrying Vessels, iii)

¹ Direct Passing Vessel describes a vessel planned not to call any port, berth or place within the Turkish Straits Region, and reported the same in her Sailing Plan to the Turkish authorities before entering to the Straits.

² Indirect Passing Vessel describes a vessel planned to call a port, berth or place within the Turkish Straits Region, or a vessel whose direct passing has been cancelled or interrupted.

Hazardous Material (HazMat) Carrying Vessels, iv) Tankers and v) General Cargo Carrying Vessels.

On the other hand, there are 7 length groups regarding the application of the Rules. The total number and frequency distribution of vessels transited in the year 2005 based on these classifications are displayed in Table 3.1 and Table 3.2 respectively. The last length group (length > 300 meters) does not exist in the table since there were no such vessels in 2005 data.

Table 3.1. Number of vessels transited in 2005 (Source: TSVTS)

Type / Length (meter)	< 50	50 - 100	100 - 150	150 - 200	200 - 250	250 - 300	Total in type
<i>Passenger</i>	96	1080	235	59	26	2	1498
<i>LNG-LPG</i>		127	83	71	51		332
<i>HazMat</i>	1	225	290	220	95	14	845
<i>Tanker</i>	5	2716	2038	2369	1321	712	9161
<i>General Cargo</i>	482	16905	19488	4795	1167	117	42954
Total in length	576	20960	22115	7509	2658	845	54790

Table 3.2. Frequency distribution of vessels transited in 2005 (Source: TSVTS)

Type / Length (meter)	< 50	50 - 100	100 - 150	150 - 200	200 - 250	250 - 300	Total in type
<i>Passenger</i>	0.002	0.020	0.004	0.001	0.0005	0.00004	0.027
<i>LNG-LPG</i>		0.002	0.002	0.001	0.001		0.006
<i>HazMat</i>	0.00002	0.004	0.005	0.004	0.002	0.0003	0.015
<i>Tanker</i>	0.00009	0.050	0.037	0.043	0.024	0.013	0.167
<i>General Cargo</i>	0.009	0.309	0.356	0.088	0.021	0.002	0.784
Total in length	0.011	0.383	0.404	0.137	0.049	0.015	1.000

Interarrival times of vessels are independently analyzed according to vessel types, vessel lengths and entrance direction of vessels to the Strait. For Passenger vessels, interarrival times are analyzed separately for entrance direction and direct/ indirect passing status. For each cluster, appropriate probability distributions regarding their interarrival times are fitted through the Input Analyzer module of Arena. The resulting distributions and information regarding their goodness of fit are presented in Table A.1 and Table A.3.

For instance, the histogram and the fitted distribution summary regarding the interarrival times (in minutes) of 245 southbound general cargo vessels less than 50 meters of length is given in Figure 3.1 and Table 3.3 respectively.

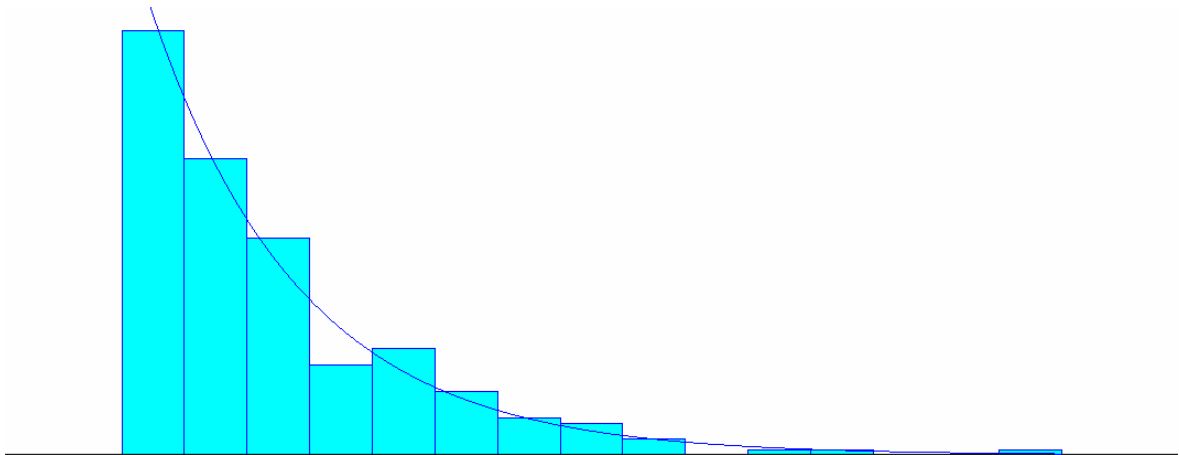


Figure 3.1. The histogram of interarrival times of southbound general cargo vessels length below 50 meters

Table 3.3. The Input Analyzer distribution fit summary for interarrival times of southbound general cargo vessels length below 50 meters (in minutes)

<i>Distribution:</i>	Exponential
<i>Expression:</i>	EXPO(2.12e+003)
<i>Square Error:</i>	0.001837
<i>Chi Square Test</i>	
<i>Number of intervals</i>	7
<i>Degrees of freedom</i>	5
<i>Test Statistic</i>	4.39
<i>Corresponding p-value</i>	0.495
<i>Kolmogorov-Smirnov Test</i>	
<i>Test Statistic</i>	0.0305
<i>Corresponding p-value</i>	> 0.15
<i>Data Summary</i>	
<i>Number of Data Points</i>	245
<i>Min Data Value</i>	0.417
<i>Max Data Value</i>	13300
<i>Sample Mean</i>	2120
<i>Sample Std Dev</i>	2030

As mentioned, this histogram and the distribution summary are obtained through the Input Analyzer. In this case, the Input Analyzer selected the best fit for the given interarrival data to be the exponential distribution with the scale parameter $\beta = 2120$. Even through a simple visual observation, it seems reasonable to accept the selected distribution. Besides, the p-value of the chi-square test for this fit is 0.495 and gives no reason to conclude that the interarrival time data are not suitably represented by the expo (2120)

distribution. Thus, expo (2120) is accepted as the appropriate distribution to represent the arrival process of southbound general cargo vessels of length < 50 meters.

In some of the cases, the goodness-of-fit tests have not been satisfactory. However, it is known that if there are enough data, the test will definitely reject the choice of distribution. The more data there are, the more powerful the test for detecting differences between the distribution of choice and the process data. Thus, it is suggested that goodness-of-fit test should be advisory only (Deler and Nelson, 2002).

Another example is associated with the 1189 northbound tanker vessels having length between 150 and 200 meters. The related interarrival time histogram and fitted distribution summary is given in Figure 3.2 and Table 3.4 respectively.

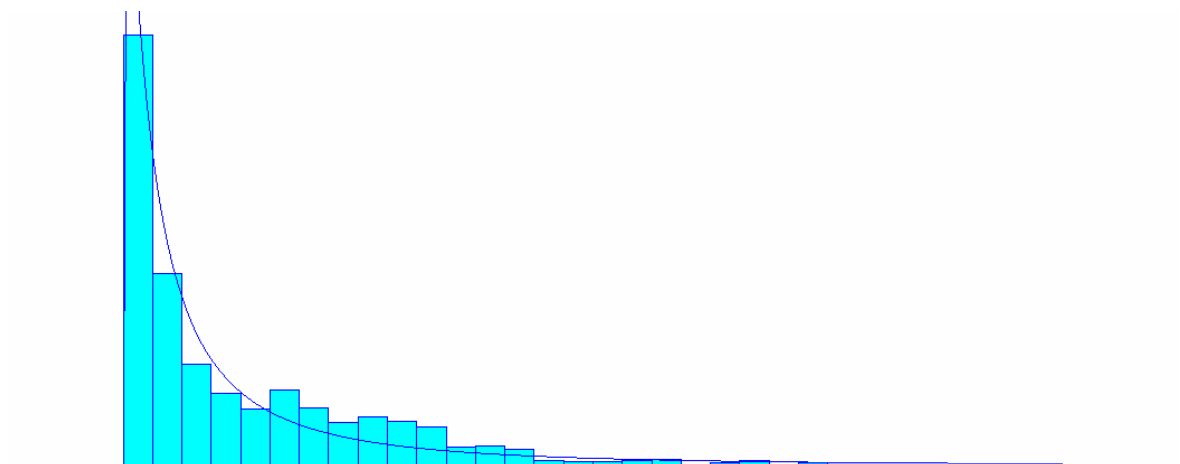


Figure 3.2. The histogram of interarrival times of northbound tanker vessels length between 150 and 200 meters

In this case, the Input Analyzer selected the best fit for the interarrival data to be the lognormal distribution with the parameters $\mu = 614$ and $\sigma^2 = 1770$. From visual observation, it seems reasonable to accept the selected distribution, but the p-value of the chi-square test for this fit is below 0.005. However, the square error of the fitted distribution is very low and there is no better fit for this data set. In addition, it can be expected that the test would reject the fitted distributions since number of data points is high. Thus, logn (614, 1770) is found sufficient to represent the arrival process of northbound tanker vessels of length between 150 and 200 meters.

Table 3.4. The Input Analyzer distribution fit summary for interarrival times of northbound tanker vessels length between 150 and 200 meters (in minutes)

<i>Distribution:</i>	Lognormal
<i>Expression:</i>	LOGN(614, 1.77e+003)
<i>Square Error:</i>	0.003871
<i>Chi Square Test</i>	
<i>Number of intervals</i>	19
<i>Degrees of freedom</i>	16
<i>Test Statistic</i>	177
<i>Corresponding p-value</i>	< 0.005
<i>Kolmogorov-Smirnov Test</i>	
<i>Test Statistic</i>	0.0743
<i>Corresponding p-value</i>	< 0.01
<i>Data Summary</i>	
<i>Number of Data Points</i>	1189
<i>Min Data Value</i>	0.283
<i>Max Data Value</i>	3530
<i>Sample Mean</i>	442
<i>Sample Std Dev</i>	495

In most of the cases in the distribution fitting process, chi-square tests are satisfied for the selected distributions. However, in few cases although chi-square tests have not been satisfied, the best fitted distributions are accepted as sufficient through square error comparisons and graphical analysis.

For the clusters that have insufficient data points to fit a distribution such as Tankers and Hazardous Material vessels which have lengths below 50 meters, uniform distribution is assumed (see Table A.1 and Table A.3).

Vessel lengths within each cluster are assumed to be uniform. After the generation of a vessel in a cluster, its length is randomly determined based on a uniform distribution whose lower and upper limits are defined by the length characteristics of that cluster.

Anchoring is not a mandatory procedure for the vessels but it depends on the vessels' needs. Frequency distribution of vessels that have anchored is calculated for each cluster (see Table A.2 and Table A.4). The random anchoring duration of each type is fitted to an appropriate probability distribution through the Input Analyzer (Table 3.5). Thus, if a

vessel is to anchor, it uses the appropriate anchoring duration distribution determined for the type it belongs (which is displayed in Table 3.5).

Table 3.5. Probability distribution of anchoring durations

<i>Type</i>	<i>Expression for anchoring time in minutes</i>
<i>Passenger</i>	$1 + \text{LOGN}(11.5, 20.7)$
<i>LNG-LPG</i>	$\text{LOGN}(14.1, 28)$
<i>HazMat</i>	$\text{LOGN}(16.9, 50.6)$
<i>Tanker</i>	$-0.001 + \text{LOGN}(12.6, 25.4)$
<i>General Cargo</i>	$-0.001 + \text{LOGN}(16.5, 42.5)$

Frequency distributions of pilot captain requests and direct/ indirect passing status of vessels are calculated for each cluster as well (see Table A.2 and Table A.4). However, since there is no information on tugboat demand in the 2005 data, a probability distribution is assumed based on the length class of vessels. The tugboat demand probabilities are assumed to be 90 per cent for vessels having length between 250 meters and 300 meters and 30 per cent for vessels having length below 250 meters. Lastly, vessels greater than 300 meters of length are assumed to be assigned two tugboats.

Speed capabilities of vessels are also analyzed based on clusters and fitted appropriate probability distributions through the Input Analyzer. In these fits, mainly triangular distribution is found to be most suitable (see Table A.5).

3.2. Treatment of Visibility Issues

The article 36 of the Maritime Traffic Regulations for the Turkish Straits and the Marmara Region (1998) on visibility states that:

“... ”

(b) When visibility in any part of the Istanbul Strait is 1 nautical mile or less, maritime traffic shall be open in the appropriate direction and closed in the opposite. In such situations, vessels carrying hazardous cargo, large vessels and deep draft vessels shall not enter into the Istanbul Strait,

(c) When visibility in any part of the Istanbul Strait is less than 0.5 nautical miles, the traffic flow in the Istanbul Strait shall be closed in both directions.

...”

Stochastic analysis of fog occurrences and the resulting visibility conditions in the Strait of Istanbul is named as the visibility submodel. Visibility submodel is based on data from different sources. These data sources are:

- Historical visibility data of the last 17 years obtained from the Kandilli Observatory and Earthquake Research Institute (KOERI),
- Historical visibility data of the last 4 years obtained from the International Weather Information Web-site “www.weatherunderground.com” (WU),
- Actual Strait of Istanbul closures due to bad visibility for the years 2004 – 2005, obtained from the Coastal Safety and Salvage Administration.

In modeling of visibility conditions these data sources are used for different purposes. The KOERI data are used to capture the seasonal effects and to model fog occurrences in fall/spring and summer seasons, whereas the Weather Underground data are used to model interarrival times of fog occurrences in the winter season and durations of fog occurrences for all seasons. Furthermore, closure data of the Coastal Safety are used in mapping the decision flow of the Strait Authority for the closure of the Strait due to visibility conditions.

3.2.1. The Kandilli Observatory Visibility Data

In the KOERI data, for each day there are 3 observations taken at 07:00 in the morning, 14:00 in the afternoon and 21:00 at night. These observations giving the visibility conditions in kilometers are converted to binary representation of fog realizations necessitating closure of Strait (based on the Regulations); 1 for fog and 0 for clear sight. The resulting count of fog realizations on monthly and yearly basis are given in Table 3.6. This table clearly highlights the seasonal visibility variation among months.

Table 3.6. Number of monthly fog realizations over 17 years in the KOERI data

Month / Year	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2003	2004	Average
January	3	2	2	4	5	0	5	6	0	0	3	3	2	7	9	3	0	3	3.17
February	6	13	14	2	0	1	0	2	6	3	6	7	5	1	7	2	0	5	4.44
March	9	6	11	8	0	6	0	8	2	1	1	0	2	0	0	2	1	6	3.5
April	14	3	4	3	2	1	0	5	1	1	1	0	8	4	4	2	2	2	3.17
May	2	3	1	1	0	0	0	0	1	4	1	1	4	1	1	0	0	2	1.22
June	2	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0.22
July	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0.17
August	3	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	1	0.39
September	2	3	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0.44
October	0	2	0	0	0	1	0	2	0	1	0	0	1	0	1	1	0	4	0.72
November	1	3	3	3	1	2	0	5	2	0	2	3	6	0	1	1	7	3	2.39
December	3	4	2	4	2	4	0	1	2	4	3	0	0	2	0	0	2	1	1.89
Total	46	39	38	25	10	16	6	29	14	17	17	16	28	16	23	11	12	28	21.7

To smooth out the seasonality effect, moving average of 31 days of the daily fog occurrence frequency distribution is plotted in Figure 3.3. This frequency distribution of daily fog occurrences is calculated by the number of fogs observed on each day in 17 years.

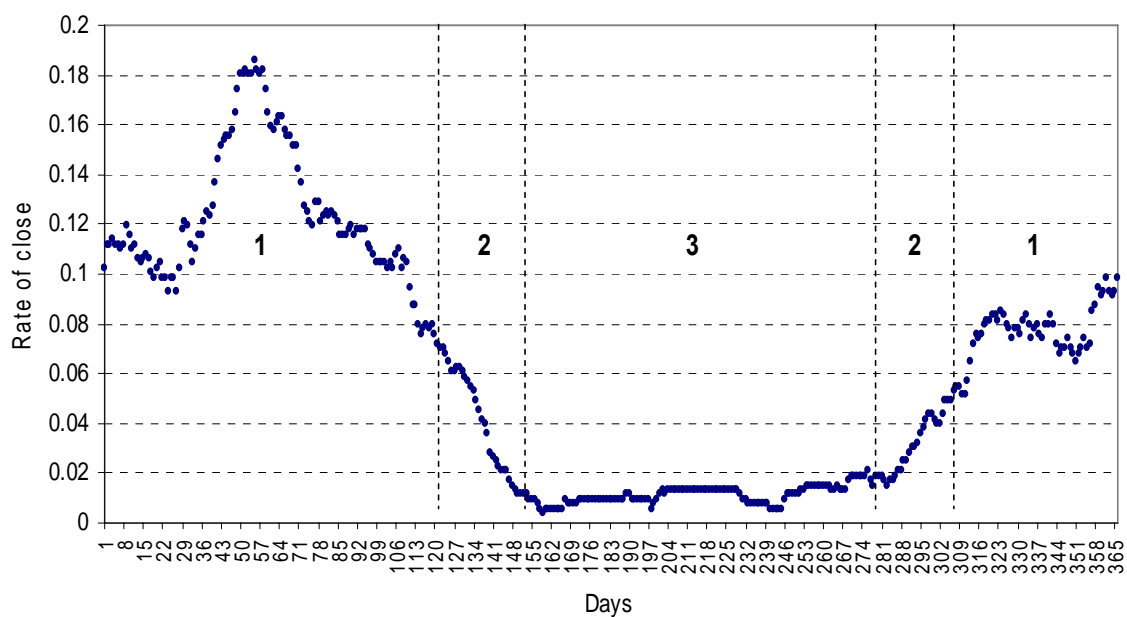


Figure 3.3. Frequency distribution of daily fog occurrences over 17 years in the KOERI data – moving averages of 31 days

Based on this plot, a year is classified into 3 seasons. These seasons are (1) winter, (2) fall/spring and (3) summer. The months that fall in these seasons are shown in Table 3.7.

Table 3.7. Visibility seasons

<i>(1) Winter</i>	<i>(2) Fall / Spring</i>	<i>(3) Summer</i>
November	May	June
December	October	July
January		August
February		September
March		
April		

3.2.2. The Weather Underground Visibility Data

The Weather Underground (WU) data comprise of observations taken in half-hour intervals for the years 2001 to 2005. The original observations giving the visible distance in kilometers are converted to binary representations of fog realizations necessitating closure of the Strait; 1 for fog and 0 for clear sight. Since these observations are recorded at half-hour periods, there is sufficient data to assess the probabilistic representation of start times and durations of fog occurrences.

As can be seen in Figure 3.4, the frequency distribution of fog start times based on WU data indicates that while fog starts fluctuate throughout a day they are far more frequent at night time than at daytime.

The fluctuations around close time points in Figure 3.4 may be explained by lack of data, since WU data comprise of 107 fog observations in 5 years time. Unfortunately, no appropriate closed form probability distribution could be fitted to this set of highly fluctuating data. So, the rough but simple probability distribution displayed in Figure 3.5 is assumed.

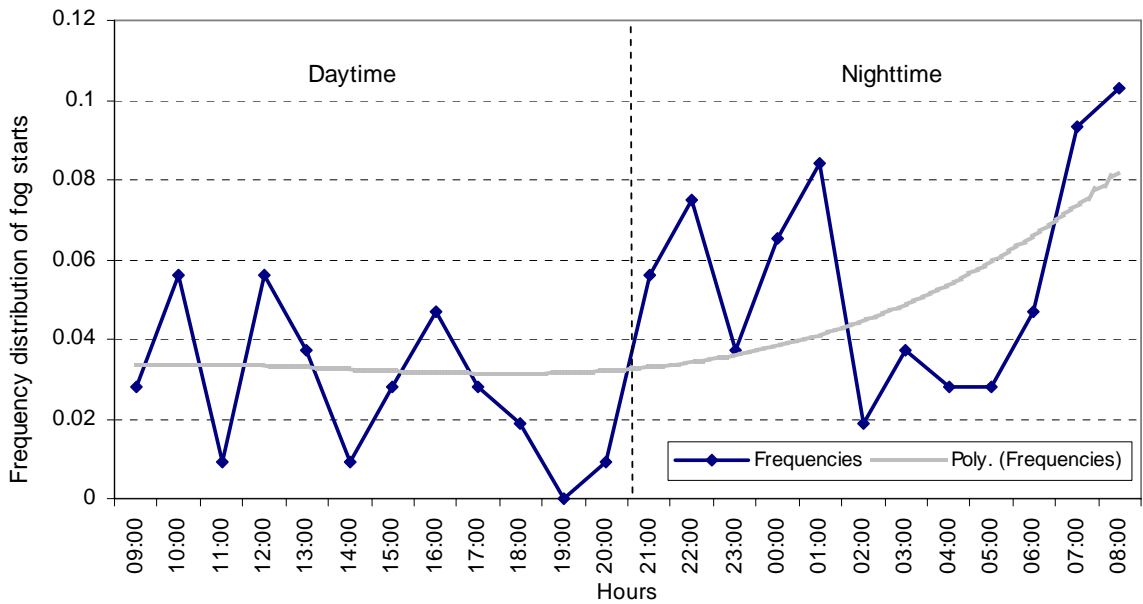


Figure 3.4. Realized frequency distribution of fog starts in hours of day in the KOERI data

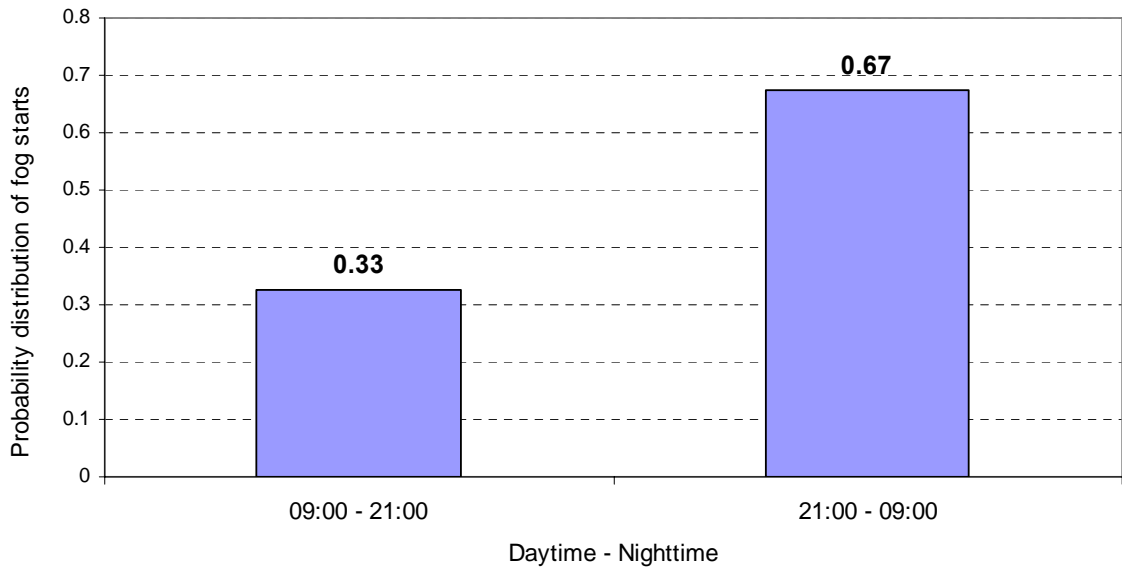


Figure 3.5. The assumed probability distribution of fog starts in daytime and nighttime

Apart from fog start times, the likelihood of the existence of fog at any given time throughout the day is another important characteristic (Figure 3.6). These observations on fog existence also convey information on fog duration besides fog starts. Figure 3.6 indicates that fog occurrences are far more frequent at night time than at daytime consistent with the fog start time distribution.

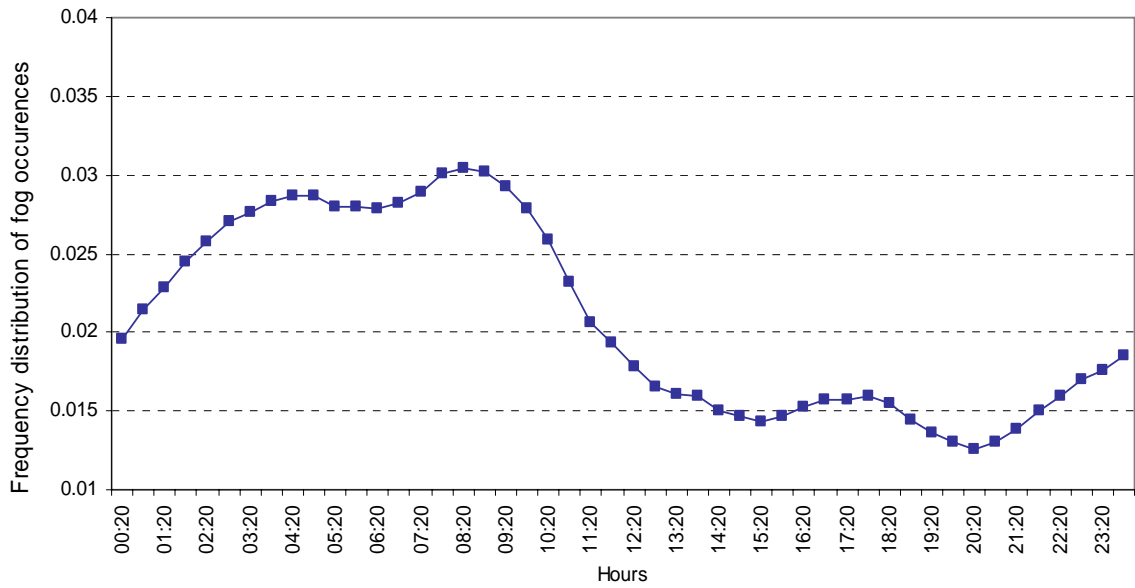


Figure 3.6. Frequency distribution of fog occurrences in hours of day in the KOERI data - moving averages of 5 periods (2.5 hours)

As displayed in Figure 3.7, it is also checked whether fog durations have a relation with fog start times. Trend line in Figure 3.7 indicates that fogs that start at night time have a little longer duration than the fogs that start in day time. However, this relation is quite weak and thus it is assumed that fog durations are independent from the start times of fogs.

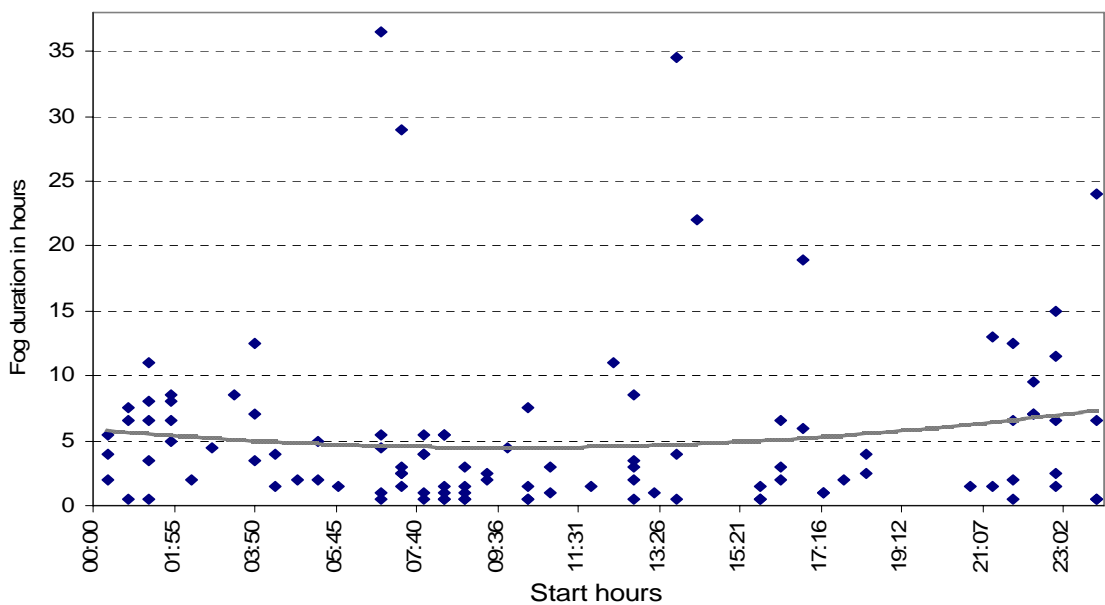


Figure 3.7. The scatter diagram of fog starts versus fog durations in KOERI data

3.2.3. Closure of the Strait Data of the Coastal Safety Administration

Coastal Safety data include the actual time intervals in which the Strait of Istanbul have been closed, between April 2004 and April 2005. Since the period of data is very limited, it was not possible to base the estimates of fog arrival and duration distributions, neither seasonality trends on these data. However, this data set contains important information on closure patterns of the Strait of Istanbul and thus could be used to confirm data from other sources or to validate the developed models.

Apart from the 2004-2005 data, the closure duration information of the Strait of Istanbul since 1995 has also been accessed (Table 3.8). This data is also converted into frequencies of one-way (northbound or southbound) and two-way (total) closures of the Strait due to fog (the Strait can be closed for one-way or two-way according to the intensity of fog) (Table 3.9).

Table 3.8. Actual closure times of the Strait of Istanbul due to visibility in hours

<i>Close Direction</i>	<i>1995</i>	<i>1997</i>	<i>1998</i>	<i>1999</i>	<i>2002</i>	<i>2003</i>	<i>2004</i>	<i>2005</i>	<i>AVG</i>	<i>Stdev</i>
<i>North-South</i>	12.05	10.35	11.4	17.25	15.4	20.5	4	13.7	13.08	4.96
<i>South-North</i>	11.4	8.55	14.25	6.1	10.2	5.5	2.3	33.5	11.48	9.65
<i>Two-Way</i>	166.55	120.5	198.45	83.2	181	155.55	156.8	269.3	166.42	54.86
<i>Total</i>	190.4	140.2	224.5	106.55	207	181.5	163.1	316.5	191.22	62.92

Table 3.9. Frequency distribution of closure direction of the Strait of Istanbul due to visibility

<i>Close Direction</i>	<i>1995</i>	<i>1997</i>	<i>1998</i>	<i>1999</i>	<i>2002</i>	<i>2003</i>	<i>2004</i>	<i>2005</i>	<i>AVG</i>
<i>North-South</i>	0.063	0.074	0.051	0.162	0.074	0.113	0.025	0.043	0.08
<i>South-North</i>	0.060	0.061	0.063	0.057	0.049	0.030	0.014	0.106	0.06
<i>Two-Way</i>	0.875	0.859	0.884	0.781	0.874	0.857	0.961	0.851	0.87

As a support to the fog start time assessment based on the WU data, the frequencies of the Strait closure starts (with respect to hours of day) is compiled from Coastal Safety Administration data set. Figure 3.8 displays the results, where it can be seen that Strait closure starts are more probable at night time than they are in day time.

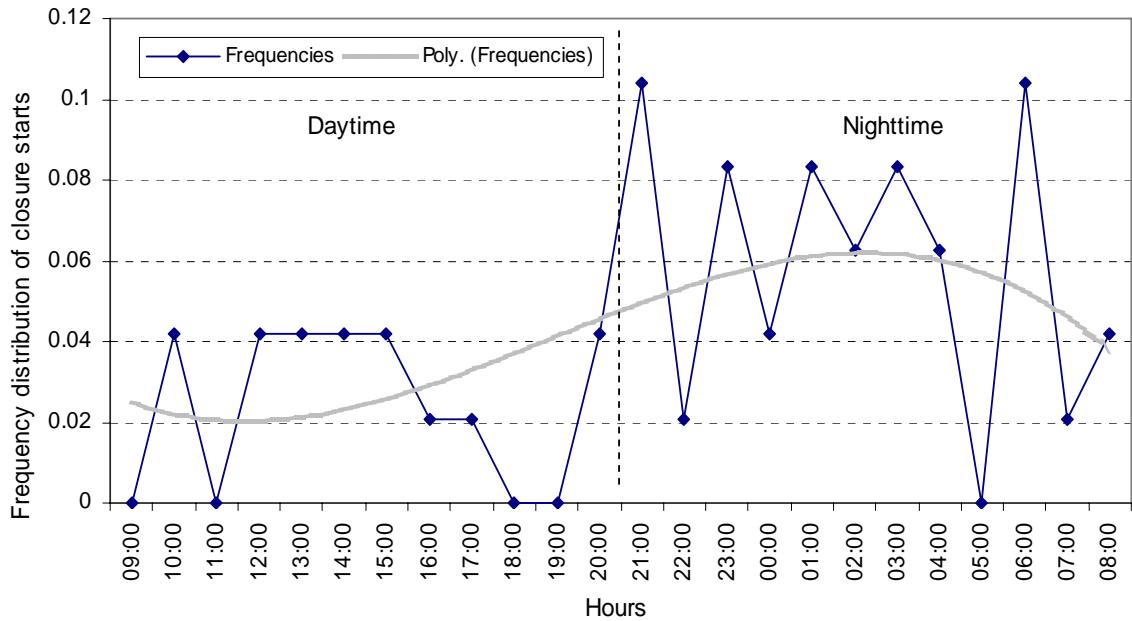


Figure 3.8. Realized frequency distribution of closure starts in hours

Again, no appropriate closed form probability distribution could be fitted to this set of highly fluctuating data. However, when the averages of overall daytime versus overall nighttime frequencies of Strait closure starts are computed, the resulting rough but simple probability distribution (displayed in Figure 3.9) highly resembles the one obtained for fog starts based on the WU data.

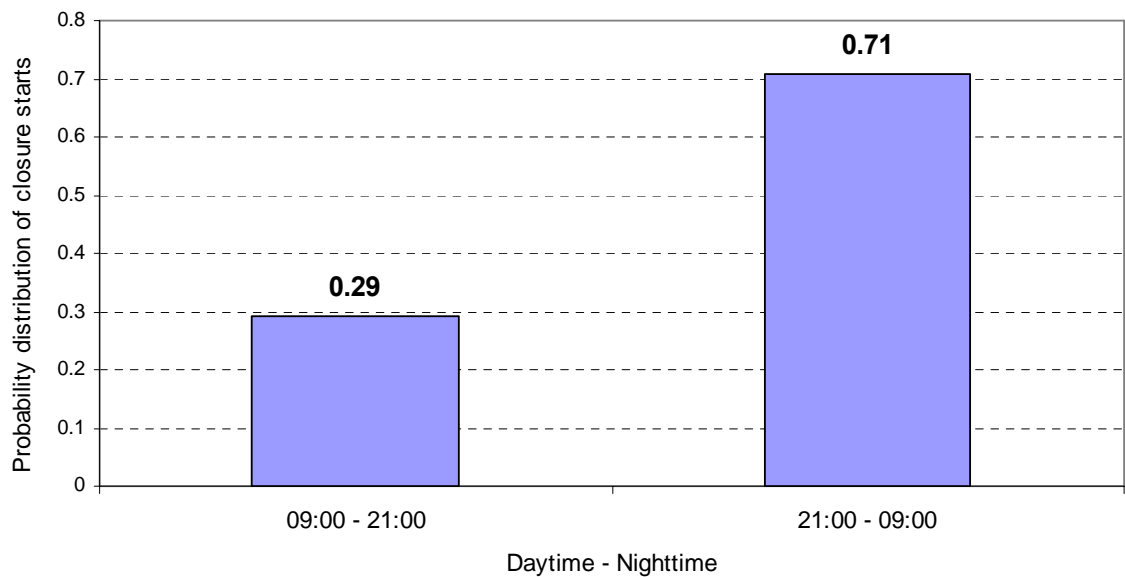


Figure 3.9. The assumed probability distribution of closure starts in daytime and nighttime

The frequency distribution of closed hours of the Strait due to poor visibility based on the Coastal Safety Administration data set is given in Figure 3.10. This figure indicates that the Strait is two times more frequently closed at night time than it is in day time.

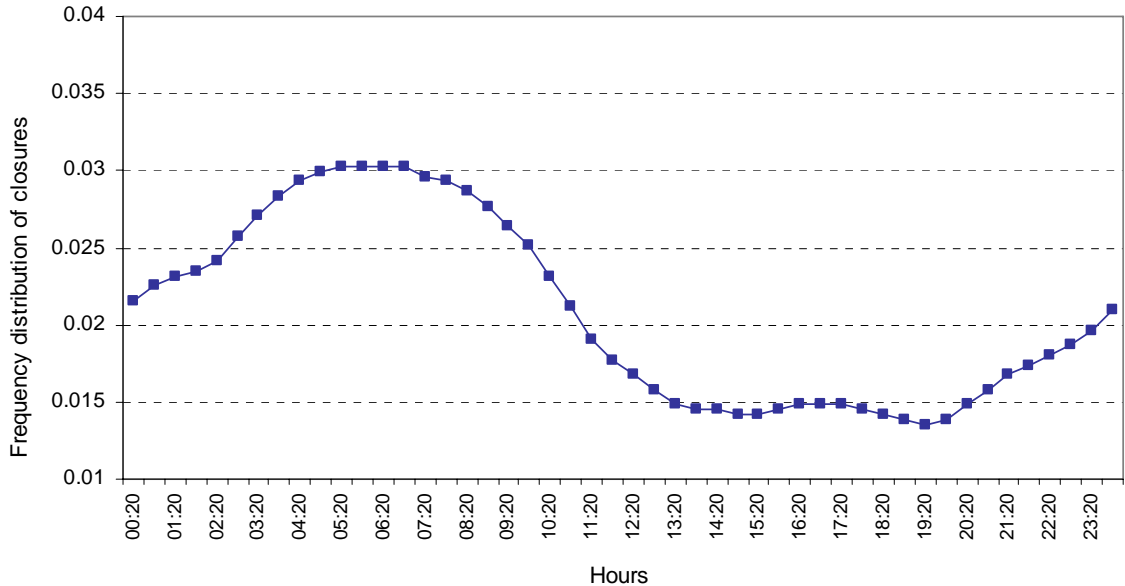


Figure 3.10. Frequency distribution of closure occurrences in different hours of day - moving averages for 5 periods (2.5 hours)

It is also checked whether closure durations of the Strait have a relation with closure start times. The trend line in Figure 3.11 indicates that closures that start at night time have little longer durations than closures that start at day time. On the other hand, this relation does not seem quite strong and thus, it is assumed that closure durations are independent from closure start times.

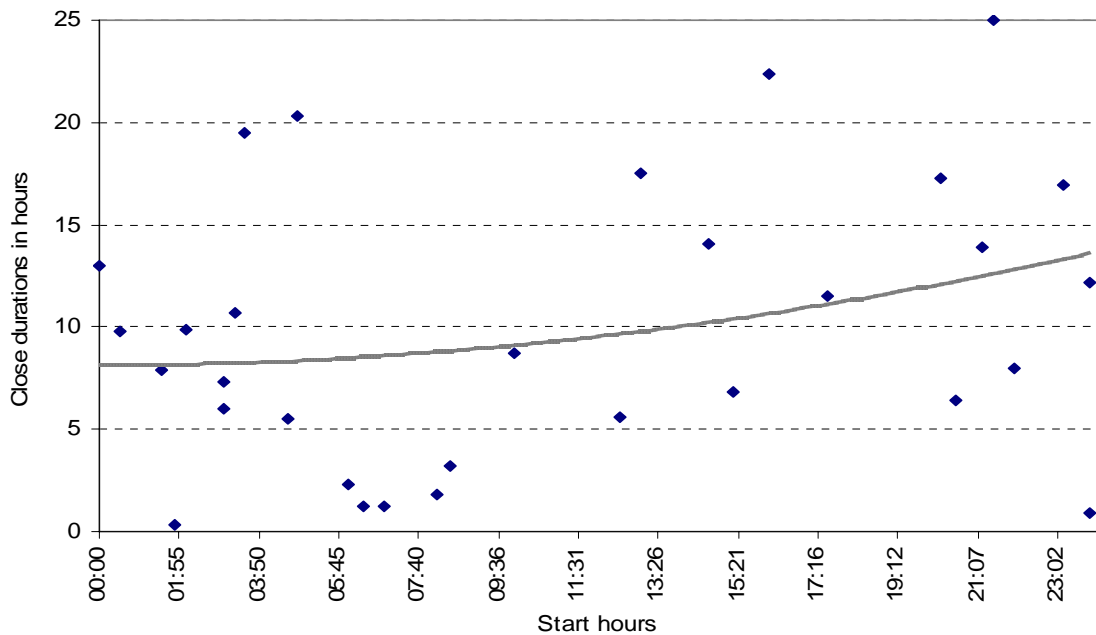


Figure 3.11. The scatter diagram of closure starts versus fog durations

3.2.4. Visibility Model – On/Off Process

The statistical analysis of past visibility data has shown a strong seasonal pattern in which low visibility levels are far more frequent in the winter season. (Actually, through statistical analysis it is observed that the initiation of dense fogs leading to low visibility levels is more frequent in the winter season.) Therefore, three probability distributions corresponding to three distinct seasons are developed to govern the random generation of daily visibility conditions throughout the Strait (again in the context of initiation of dense fog conditions). On the other hand, there is no evidence of seasonality for the duration of bad visibility conditions (i.e. dense fogs) in the data. Besides, the duration of fog events also seem to be independent from the start hour according to the WU data (Figure 3.7). Thus, the probabilistic nature of the duration of bad visibility conditions are assumed to be stationary throughout the year and phase-type distribution is used to represent the random duration of fog events, independent from the start hour, at any time of the year.

3.2.5. Modeling of Fog Initiations in the Summer and Transition Seasons

The random generation of fog initiations in the summer (June, July, August and September) and transition seasons (May and October) are based on empirical probability distributions which are given in Table 3.10 and in Table 3.11 respectively. These probabilities are based on the KOERI data since these data have a span of 17 years. In this model, for each day in the planning horizon a random variate is generated, based on the probability distribution of the related season, to decide if there is fog or not in that day.

Table 3.10. Probability distribution of June, July, August and September

<i>Status</i>	<i>Frequency</i>	<i>Probability</i>
<i>Fog</i>	21	0.010
<i>Clear</i>	2175	0.990
<i>Total</i>	2196	

Table 3.11. Probability distribution of May and October

<i>Status</i>	<i>Frequency</i>	<i>Probability</i>
<i>Fog</i>	34	0.030
<i>Clear</i>	1082	0.970
<i>Total</i>	1116	

3.2.6. Modeling of Fog Initiations in the Winter Season

The random generation of fog initiations in the winter season is based on an on/off process and is modeled through a phase type distribution. In this on/off process the system state alternates between on state and off state successively. The on state signifies good visibility conditions, whereas off state signifies bad visibility conditions. The lengths of these on/off periods are better approximated by mixtures of generalized Erlang (MGE) distributions.

For the winter season, the lengths of the on-periods (which are actually the interarrival times of fog occurrences) are generated through a phase-type distribution based on the WU data. The interarrival times and durations of fog events in the WU data are modified for the on/off process. That is, interarrival time values are transformed to the on-period lengths by subtracting the fog duration from the generated interarrival time of the

next fog event. In this context, the durations of the fog events signify the length of off-period.

Phase-type distributions have been extensively used in modeling stochastic systems and can be used to model any set of random events in principle. A phase-type distribution can be considered as the distribution of the time until absorption in a Markov chain with a single absorbing state. Numerous phase-type distributions with special structures are used in modeling stochastic systems. For instance, mixtures of generalized Erlang distributions (MGEs), which are often called Coxian distributions, have been used in the analysis of manufacturing, computer and communication systems. In principle, an MGE distribution is a mixture of the convolutions of exponential distributions (Altıok, 1997).

In order to fit the on-period data to an appropriate distribution, the data is checked for the independence assumption. The autocorrelation in the data is found to be insignificant and the on-periods are assumed to be independently and identically distributed. Actually, initially conventional distributions have been considered in which the exponential distribution showed a good fit. However, the variation in the data lead to search for a better fit than the exponential distribution.

The mean and variance of a random variable X gives a convenient measure of variability known as the squared coefficient of variation, $Cv^2_X = V[X] / E^2[X]$. If X takes values close to one another consistently, Cv^2_X is close to zero (low variability).

Cv^2 of the Erlang and the exponential distributions can only assume specific values. For instance, exponential distribution can assume $Cv^2 = 1$, whereas an MGE-2 distribution can assume any value greater than 0.5. However, these distributions are special cases of the MGE-k distribution, and it is possible to specify the parameters of an MGE-k distribution such that its Cv^2 can assume any desired value in the range $(0, \infty)$ (Altıok, 1997).

The mean, variance and squared coefficient of the on- period data are given in Table 3.12. According to the Cv^2 of the data, the on-process can be modeled better with an appropriate MGE-k distribution.

Table 3.12. Mean, variance and squared coefficient of variation of on-period data

Mean (hours)	6.77
Variance	91.24
Cv^2	1.99

The MGE-2 is the simplest distribution that is capable of modeling random phenomena with $Cv^2 > 1$. Thus, it is a good candidate to model the on-period with. To model a process with MGE distributions, Altok (1997) proposed the method of moments. That is, the required parameters can be obtained using the first three moments, m_i , $i = 1, 2, 3$. Figure 3.12 shows the representation of the MGE-2 distribution. In this figure, each of two phases is exponentially distributed with rate μ_i in phase i . The conditional probability that the process transits to phase two given that phase one is completed is abbreviated by a .

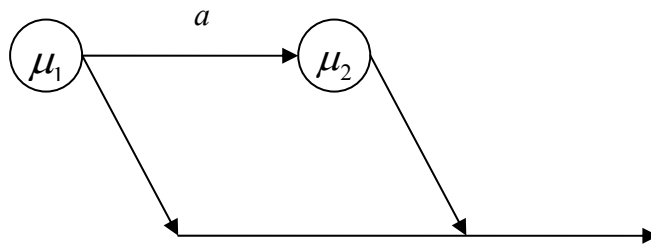


Figure 3.12. Representation of MGE-2 distribution

The first three moments of the interarrival distribution is $m_1 = 6.77$, $m_2 = 136.09$ and $m_3 = 3935$ and the squared coefficient of variation $c = 1.99$. In order to check for the appropriateness of the MGE-2 distribution, the necessary condition is

$$\frac{m_3}{m_1^3} > \frac{3}{2}(c+1)^2. \quad (3.1)$$

In our case, the necessary condition is not satisfied for the MGE-2 distribution. However, the three moment approximation can be still used at the expense of adding more phases to the MGE distribution. The smallest integer k satisfying (3.2) gives the dimension of the appropriate MGE- k distribution. Then, solving for the smaller root of α in (3.3) is sufficient to find the required parameters through equations (3.4).

$$k \geq \left(\frac{m_3 m_1}{m_2^2} - 1 \right)^{-1} \quad (3.2)$$

$$\alpha^2 [4m_1^2(k+1) - 3m_2k] + \alpha [km_3 - (4+k)m_1m_2] + (k+1)m_2^2 - km_1m_3 \quad (3.3)$$

$$\mu_1 = \frac{1}{\alpha}, \quad \mu_2 = \frac{k(m_1 - \alpha)}{m_2 - 2m_1\alpha} \quad \text{and} \quad a = \frac{k(m_1 - \alpha)^2}{(k-1)(m_2 - 2m_1\alpha)} \quad (3.4)$$

In our case, from equation (3.2), k is found to be 3. The roots of α are $\alpha_1 = 0.543$ and $\alpha_2 = 10.348$, from which $\alpha_1 = 0.543$ is to be used in the equations (3.4). Solving for the equations (3.4) leads to

$$\mu_1 = 1.842,$$

$$\mu_2 = 0.145;$$

$$a = 0.4516.$$

The representation of the appropriate MGE-3 distribution is given in Figure 3.13.

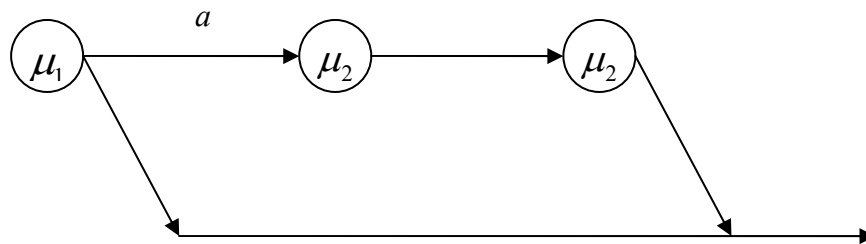


Figure 3.13. Representation of MGE-3 distribution

At the final stage of interarrival distribution fitting, goodness of fit tests showed a better fit of the interarrival data to the MGE-3 distribution than the exponential distribution. Thus, MGE-3 distribution is accepted as appropriate for the interarrival time distribution of fog events.

3.2.7. Modeling of Fog Durations

In modeling the duration of fog events, again, initially conventional distributions are considered in which the exponential distribution showed a good fit. However, the variation in the data led to search for a better fit than the exponential distribution. Accordingly, the duration of fog events (or the off-period data) is also modeled through phase-type distributions. Autocorrelation in the duration data is insignificant and the durations are assumed to be independently and identically distributed.

The mean, variance and squared coefficient of the off-period data are given in Table 3.13. In reality, the mean of the duration data is 5.23 hours. However, the minimum duration of a fog event is assumed to be 0.5 hours (which is the case in the data as well). Thus, the distribution fitting procedure is performed just for the remainder of the fog period (i.e. the distribution of the random portion of the fog period beyond the minimum of 0.5 hours) after reducing the 0.5 hours from each datum point. The Cv^2 of the data points out that the off-process can be modeled better with an appropriate MGE-k distribution.

Table 3.13. Mean, variance and squared coefficient of variation of off-period data

<i>Mean (hours)</i>	4.73
<i>Variance</i>	43.24
<i>Cv^2</i>	1.94

The MGE-2 is again the first candidate to try fitting the duration data (Figure 3.12). The required parameters can be obtained using the first three moments, m_i , $i = 1, 2, 3$. The first three moments of the duration distribution is $m_1 = 4.73$, $m_2 = 65.17$ and $m_3 = 1492.98$ and the squared coefficient of variation $c = 1.94$. In order to check for the appropriateness of the MGE-2 distribution, the necessary condition of equation (3.1) is again consulted.

Since the necessary condition is satisfied, (and both the rates and branching probability are positive) the MGE-2 distribution is regarded suitable for the duration data. The parameters μ_1 , μ_2 and a can be obtained through equations (3.5), (3.6) and (3.7).

$$a = \frac{\mu_2}{\mu_1} (m_1 \mu_1 - 1) \quad (3.5)$$

$$2m_1(\mu_1 + \mu_2) - m_2\mu_1\mu_2 = 2 \quad (3.6)$$

$$6m_1(\mu_1 + \mu_2)^2 - 6m_1\mu_1\mu_2 - 6(\mu_1 + \mu_2) - m_3\mu_1^2\mu_2^2 = 0 \quad (3.7)$$

The substitution of $X = \mu_1 + \mu_2$ and $Y = \mu_1 \mu_2$ yields

$$Y = \frac{6m_1 - 3m_2 / m_1}{(6m_2^2 / 4m_1) - m_3}, \quad (3.8)$$

$$X = \frac{1}{m_1} + \frac{m_2 Y}{2m_1}. \quad (3.9)$$

Then the values of μ_1 and μ_2 can be found through (3.10) and a can be found by (3.5).

$$\mu_1 = \frac{X + \sqrt{X^2 - 4Y}}{2} \quad \text{and} \quad \mu_2 = X - \mu_1 \quad (3.10)$$

Solving for the equations (3.10) and (3.5) leads to

$$\mu_1 = 0.7019,$$

$$\mu_2 = 0.1277;$$

$$a = 0.4217.$$

The representation of the appropriate MGE-2 distribution is given in Figure 3.12.

At the final stage of duration distribution fitting, goodness of fit tests showed a better fit of the duration data to the MGE-2 distribution than to the exponential distribution. Thus, MGE-2 distribution is accepted as appropriate for the random representation of fog durations (once a fog event has started).

3.2.8. Closure Pattern on Fog Occurrences

So far, visibility conditions in the Strait of Istanbul are analyzed through fog events, according to the data of fog occurrences in hand. However, visibility conditions affect the traffic in the Strait not only through the frequency and the duration, but also through the intensity of fog events.

The Strait Regulations obligate that when visibility drops to 1 nautical mile or less in any area within the Strait, vessel traffic shall be permitted in one direction only, and when visibility drops to less than 0.5 nautical mile, vessel traffic shall be suspended in both directions.

Nevertheless, the visibility data in hand do not match with the Coastal Safety Administration's Strait closure data. The main reasons of that are the sensitivity and accuracy problems both in the original recording of the visibility data and in the interpretation of the actual fog realizations by the Strait Authority (in triggering the closures of the Strait due to sometimes subjective tolerance limits).

On the other hand, the WU data shows another important property of fog events. As displayed in Figure 3.14, lengths of fog durations have about 24 per cent correlation about with the visibility range.

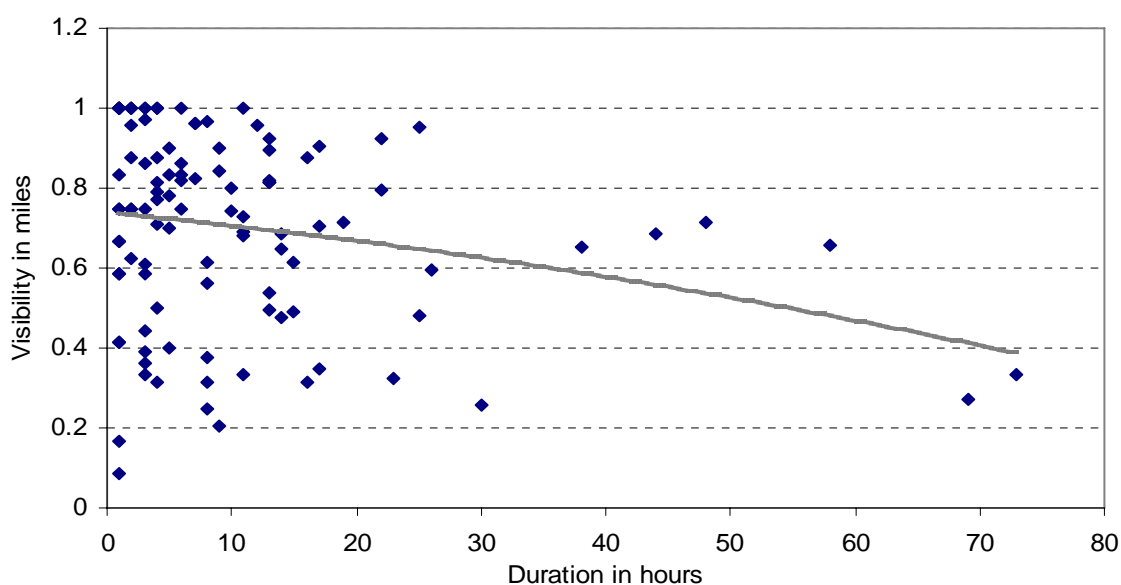


Figure 3.14. The scatter diagram of visibility in miles versus fog durations

Furthermore, the closure pattern in the Coastal Safety data points out the application of safety limits and procedures towards fog events. That is, the Strait Authority uses a multi-stage procedure in regard to triggering closures of the Strait due to fog events. The data indicate that for long fog events, the Strait is closed successively first in one direction and then in both directions. Besides, the actual closure duration exceeds the real fog duration in most of the cases. The reason behind this behavior is again safety considerations (i.e. to be sure that fog has really ended and ordinary traffic can be resumed).

Consequently, the closure patterns and procedures to implement in the simulation model under fog occurrences are determined in the light of these information and through expert opinion. The decision flow regarding the Strait closure procedure is given in Figure 3.15. This decision procedure is further calibrated based on the number of closures and closure duration rates in the past statistics.

According to the decision flow, when the fog duration is less than six hours only a single-stage closure of the Strait is implemented. In this case, the southbound traffic can be stopped with probability $p_1 = 0.15$, or the northbound traffic can be stopped with probability $p_2 = 0.15$, or two-way traffic can be stopped with probability $p_3 = 0.7$. If the duration of the fog is longer than six hours then either a three-stage or a two-stage or a one-stage closure procedure can be applied with probabilities $p_1 = 0.4$, $p_2 = 0.4$ and $p_3 = 0.2$ respectively. Then, the total fog duration is allocated to the individual stages in the relevant procedure. For instance, in the three-stage closure, first one-way is closed for 10 per cent of the duration, then two-way is closed for 80 per cent of the duration and at last again one-way is closed for 10 per cent of the duration.

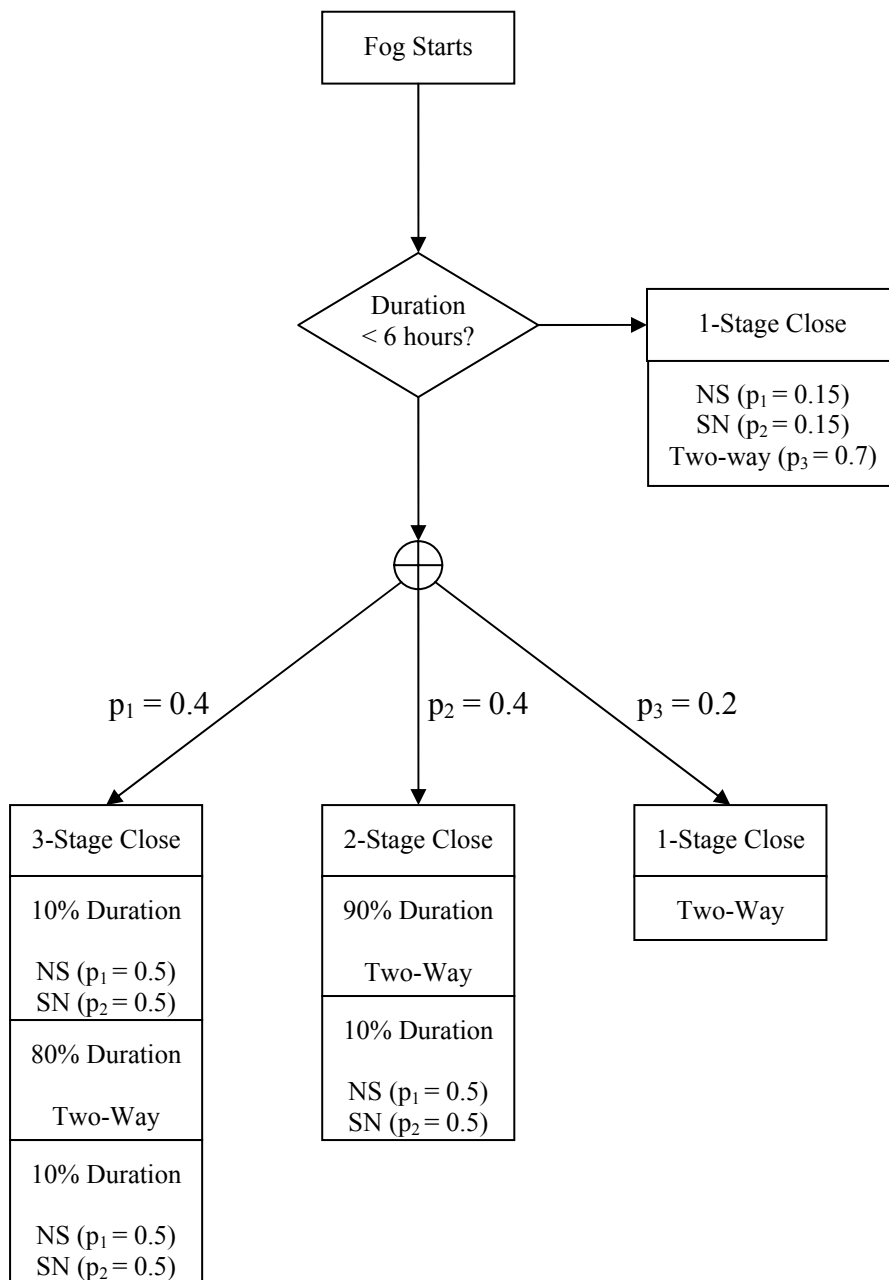


Figure 3.15. Decision flow of Strait Authority on fog occurrence

3.2.9. The Visibility Submodel in Arena

All the statistical analysis and modeling efforts discussed in the preceding sections are incorporated to the main traffic simulation model through an appropriate Arena 9.0 submodel. Probability distributions for three seasons, regarding fog start times, duration distributions and closure patterns on fog occurrences are all included in this submodel.

The duration distribution based on the WU data is modeled through phase-type distributions. However, due to the safety extension adopted by the Strait Authority, the duration of fog events are enlarged by 25 per cent before they are applied as closure durations.

3.2.10. Verification and Validation of the Visibility Model

The developed visibility model is to be integrated in the Strait Traffic model. However, before integrating the model the verification and validation should be checked. Since the model is based on different data sources on different aspects, there is not a complete data to check the overall validity of the model. However, some outputs of the model can be compared to relevant sources in hand.

Figure 3.16 displays the average daily realization of fog events over 50 replication runs of the visibility model discussed above. This figure shows the probability of a fog event in a specific day in the long run. The probability distribution for the winter days is around 0.12, for the transition seasons between 0.08 and 0.02 and for the summer days below 0.02. This structure is very similar to the case in Figure 3.3, which shows the frequency distribution of actual daily fog occurrences, as adopted from the KOERI data. The figure based on KOERI data is also represented in Figure 3.16. The only major difference between these figures is the peak in the second month. However, this is due to the stationary assumption of fog occurrences, along the months of a single season. That is, the simulation runs should give the same average fog realizations for the months in the same season in the long run.

The seasonality in the visibility model can also be seen through Figure 3.17. In this figure numbers of monthly fog events are given through the average of 50 replication runs.

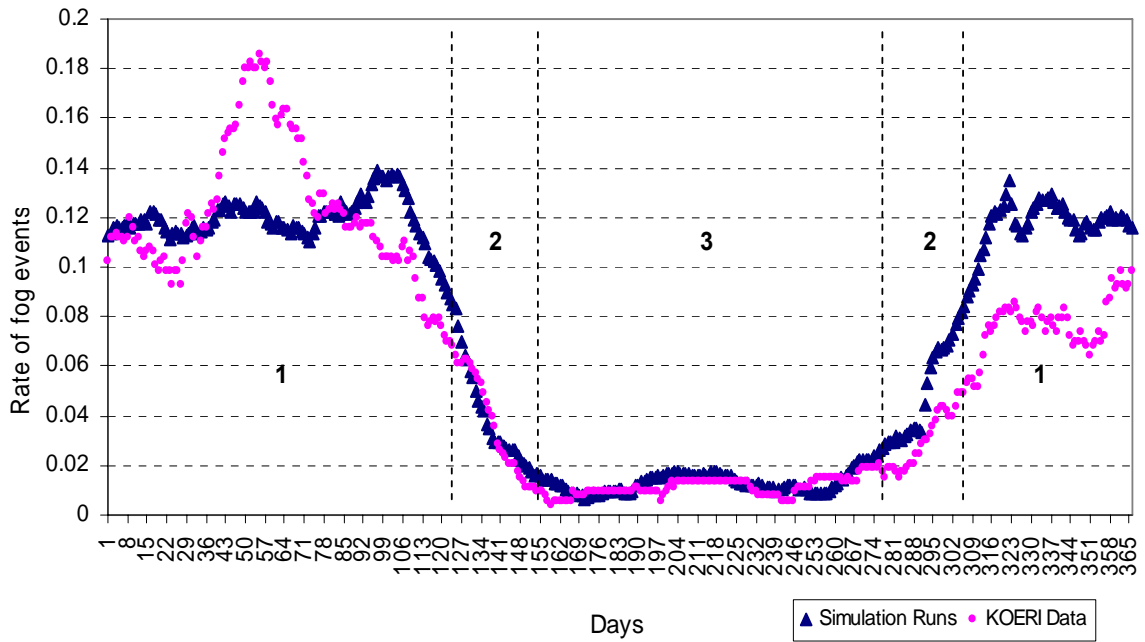


Figure 3.16. Average daily fog realizations over 50 replications – moving averages of 31 days

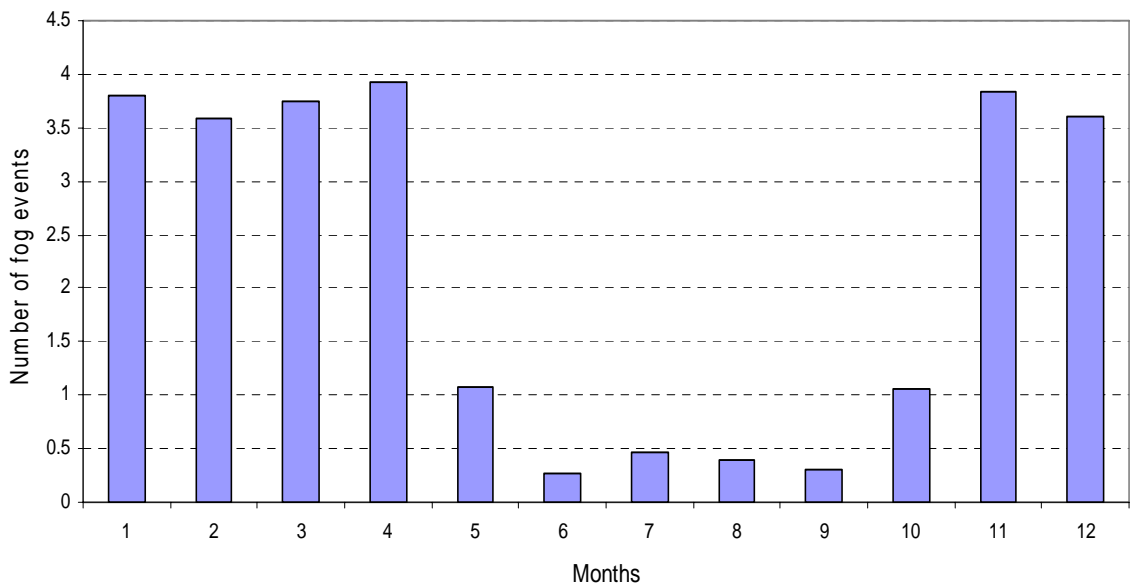


Figure 3.17. Annual fog realizations based on the developed model (average of 50 replications)

The average fog durations, lower and upper confidence levels in months are given in Figure 3.18.

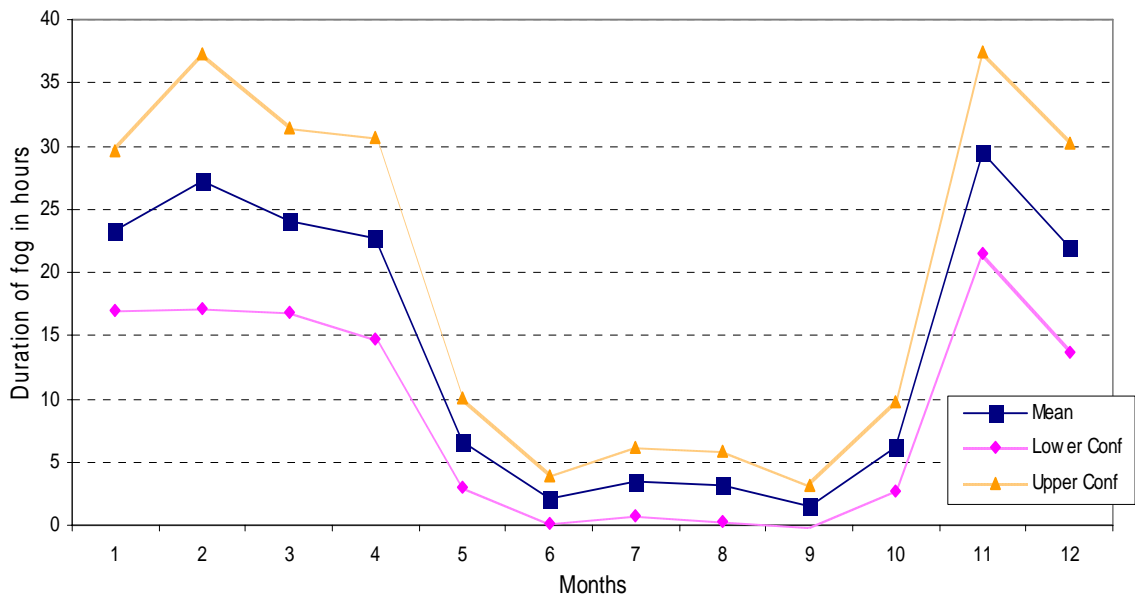


Figure 3.18. Monthly averages of fog durations based on the developed model (average of 50 replications)

The only long term data to compare the yearly total closure durations (total Strait and single directions) is the Coastal Safety data (Table 3.8 and Table 3.9). According to Table 3.14, mean and standard deviation of 50 replications on total closure of the Strait is close to the average and standard deviation of the real data. Besides, the 99 per cent t-confidence interval of the mean for 50 replications includes the actual real average of 191.22 hours.

In addition, rates of closure by direction, based on the average durations obtained in the 50 replication runs are very close to the rates observed in the real data. In real data (Table 3.9), the one-way closures are about 0.08 and two-way closures are about 0.86 which are very close to the 50 replication results.

Table 3.14. The Strait closure outputs of 50 replications

<i>Closure Direction</i>	<i>Mean (hours)</i>	<i>Std dev</i>	<i>Lower confidence</i>	<i>Upper confidence</i>	<i>Rate</i>
<i>North-South</i>	14.06	6.28	11.68	16.43	0.082
<i>South-North</i>	13.84	6.01	11.56	16.11	0.081
<i>Two-Way</i>	143.83	48.06	125.62	162.03	0.838
<i>Total</i>	171.72	55.64	150.64	192.79	1

In the WU data (Figure 3.5), the frequency distribution of fog starts in daytime and in nighttime are 0.33 and 0.67 respectively. In the visibility model, fog arrivals are distributed to day hours and night hours according to the findings from the WU and the Coastal Safety data. Thus, the trend line in Figure 3.19 matches with Figure 3.8 and verifies that the probability of a fog arrival in a specified hour in daytime is around 0.028, and 0.056 at nighttime (in total 0.33 for daytime and 0.67 for nighttime).

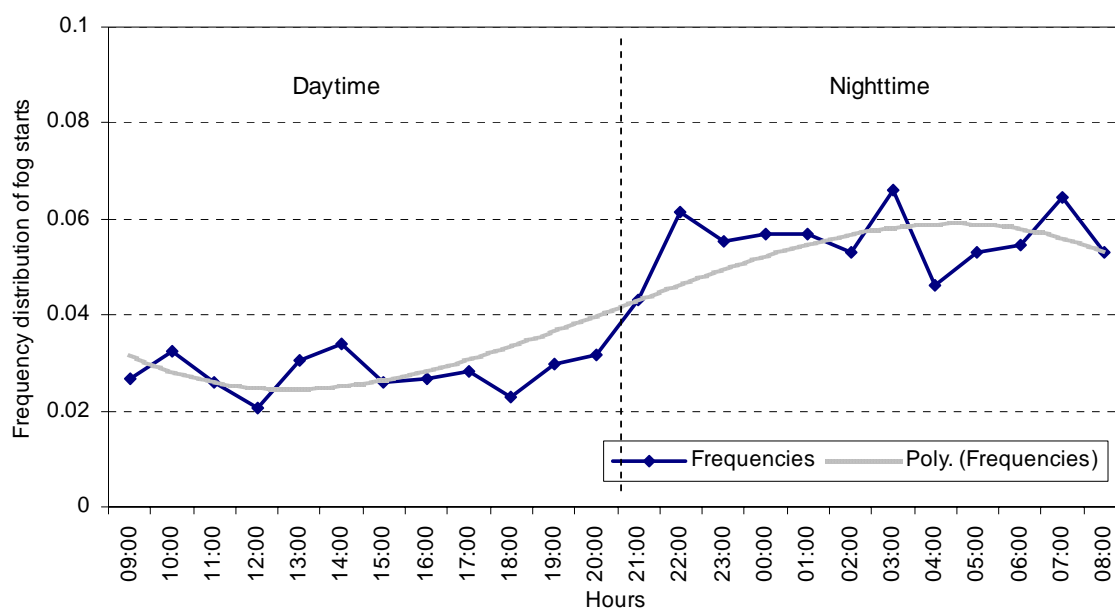


Figure 3.19. Frequency distribution of fog arrivals in hours of day in the 50 replication runs

Another important statistic obtained from the WU and the Coastal Safety data is the frequencies of fog realizations and closures of the Strait in different hours of day. These statistics are influenced both by fog / closure starts and by fog / closure durations. Both the actual data and the visibility model results associated with the frequency of closure occurrences observed in different hours of day are given in Figure 3.20. In both data sets the Strait is more frequently closed at night hours than it is in day hours. However, day / night difference in the model results is not distinct as it is in the Coastal Safety data. This may be due to the very limited data from which probability distribution of fog starts in day and night hours are adopted.

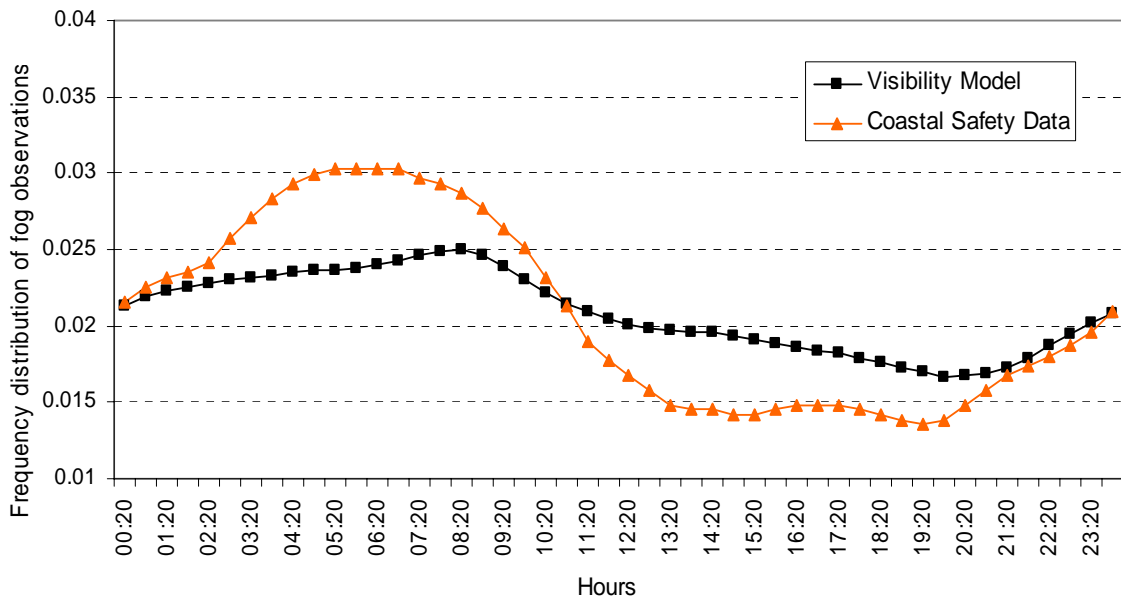


Figure 3.20. Frequency distribution of closure occurrences in different hours of day - moving averages for 5 periods (2.5 hours)

3.3. The Modeling of the Strait Surface Currents

The currents in the Strait of Istanbul have intricate characteristics that depend on the topography and coastal features of its banks, revealing eddies and reversing currents and also to the turbulent meandering of the main current (Özsoy et al., 2002).

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.

The article 35 of the Maritime Traffic Regulations for the Turkish Straits and the Marmara Region (1998) states that:

“(a) When the main surface current exceeds four knots or when southern winds reverse the main current in the Istanbul Straits, all vessels with dangerous cargo, large vessels and deep draft vessels with a speed of 10 knots or less shall not enter the Straits.

Such vessels shall wait until the speed of the current drops to four knots or less or the reverse currents disappear.

However, vessels other than those listed above may pass through the Straits by taking tugs, as advised by the Traffic Control Center.

(b) When the main surface current exceeds six knots or strong northerly currents and eddies are caused by southerly winds, all vessels with dangerous cargo, large and deep draft, regardless of their speed, shall not enter the Istanbul Strait and shall wait until the current speed falls below six knots or strong reverse currents disappear.

...”

In this study, southbound surface current, which is the main current regime in the Strait, and the reverse surface current are taken into consideration. As seen in the above quoted regulation, the importance of including surface currents to the model are due to the effects of the maximum current magnitude on acceptance of vessels into the Strait and also due to the direct effects of current magnitude on realized speeds of vessels in the Strait. Besides, a detailed analysis of current behavior throughout the Strait will assist to a prospective risk study of the Strait of Istanbul.

3.3.1. The Current Data

The current modeling undertaken is based on several data sources and on previous studies. The base current magnitude is estimated based on the historical data from the Vessel Traffic Services (VTS) and from the Turkish Navy Department of Navigation, Hydrography and Oceanography (which is adopted from a previous study).

The VTS current data comprises of daily current values observed at four different stations at the Strait of Istanbul (which are at Üsküdar, Kanlıca, Rumeli Kavak and Garipçe) for a six month period. The descriptive statistics of that data are given in Table 3.15. According to the means and variances of the data from those four stations, there are significant fluctuations of current magnitudes throughout the Strait.

Table 3.15. Means and variances of the VTS current data (in knots)

	<i>Üsküdar</i>	<i>Kanlıca</i>	<i>Rumeli Kavak</i>	<i>Garipçe</i>
<i>mean</i>	2.361	1.282	1.372	1.064
<i>variance</i>	0.442	0.150	0.243	0.120

Correlation matrix given in Table 3.16 indicates that the current magnitudes show strong correlations among successive stations. That is, Kanlıca station shows 90 per cent correlation with Rumeli Kavak station which is nearby, but shows 69 per cent correlation with Üsküdar station which is relatively far away. Thus, it can be derived that current pattern is strongly correlated throughout the Strait.

Likewise, Özsoy et al. (2002) compute the correlations between current components along the Strait as a function of the distance between pairs of data points, to reveal the structural relationships of currents. The results indicated lengthwise correlations on distances comparable to the length of the Strait, as expected for such conduit type flows.

Table 3.16. Correlation matrix of current magnitudes among four stations

	<i>Üsküdar</i>	<i>Kanlıca</i>	<i>Rumeli Kavak</i>
<i>Kanlıca</i>	0.69		
<i>Rumeli Kavak</i>	0.60	0.90	
<i>Garipçe</i>	0.55	0.75	0.80

Based on these strong correlations among the current values realized at different points of the Strait, it is assumed in this study that the daily current magnitudes in the Strait can be generated through a single base value and can be distributed to the entire Strait by using predetermined percentage factors for different locations along the Strait.

In order to determine appropriate percentage factors (of the base current value for different locations along the Strait) a set of data, which were also used in a previous study of Yazıcı (2002), are adopted (Figure 3.21). The data mentioned were observed through sailing a research boat along the Strait and taking measurements within few cables distances from north to south.

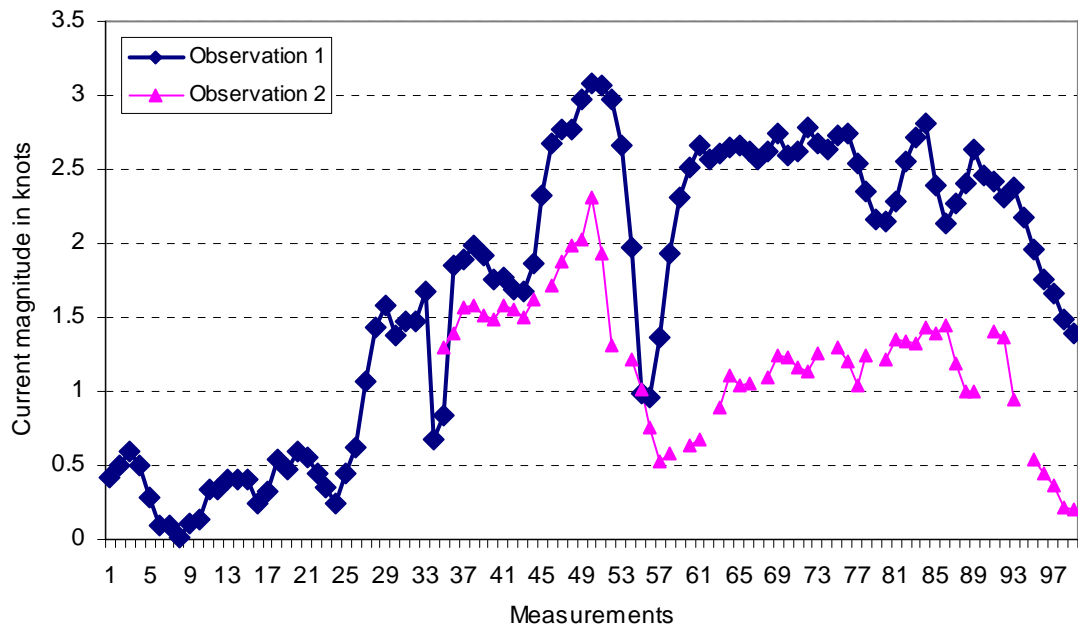


Figure 3.21. Current magnitudes throughout the Strait from north to south

There are two sets of data in Figure 3.21, which show a similar trend and (in the scarcity of data) support the assumption that current magnitudes in different points can be seen as relative proportions of each other.

The first observation set in Figure 3.21 is projected to 21 stations (which represent the entire Strait in the traffic simulation model) through averaging the measurements in each corresponding station. Then, those projected values are normalized with respect to the base station (which will be used to generate daily base values) to attain percentage factors for each station (Figure 3.22). Those percentage factors are used in the simulation model as vertical factors (v_i).

In order to determine the daily base current value (A_t), the VTS Üsküdar station data is considered. Üsküdar station has the most uninterrupted data among other stations. In addition, the mean of the current magnitudes of the VTS data at Üsküdar station is very close to the average current magnitude of station 18 (which corresponds to the Üsküdar region in the simulation model) displayed in Figure 3.22. Thus, station 18 is adopted as the base station and the percentage factors are calculated with respect to this station (Figure 3.22).

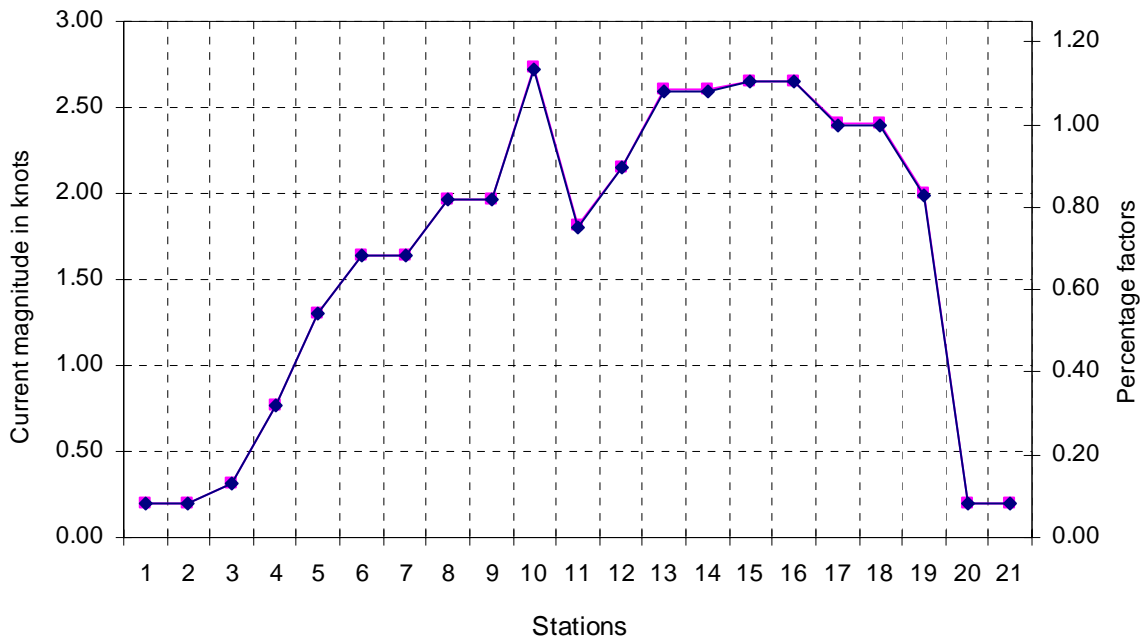


Figure 3.22. Average current magnitudes and percentage factors along stations throughout the Strait from north to south

In the model a horizontal current magnitude deviation factor is also considered. In other words, based on discussions with various experts, it is assumed that current magnitude along one Strait slice (from the European shore to the Asian shore) shows a certain variation, with attaining the relative peak value at the center (of the slice).

Each station slice in the simulation model comprises of three lanes, (where the ones near the shores correspond to the main northbound and southbound lanes and the one in the middle corresponds to the overtake lane (Figure 3.23)). So far, current magnitudes are thought to be formed in the middle of each station slice. The current magnitude derived for a particular slice (as a proportion of the overall daily base value as discussed above) is assigned to the central lane. Then, 75 per cent (which is formalized as the horizontal rate, h_j) of that current value is assigned to the northbound and southbound lanes nearer to the shores.

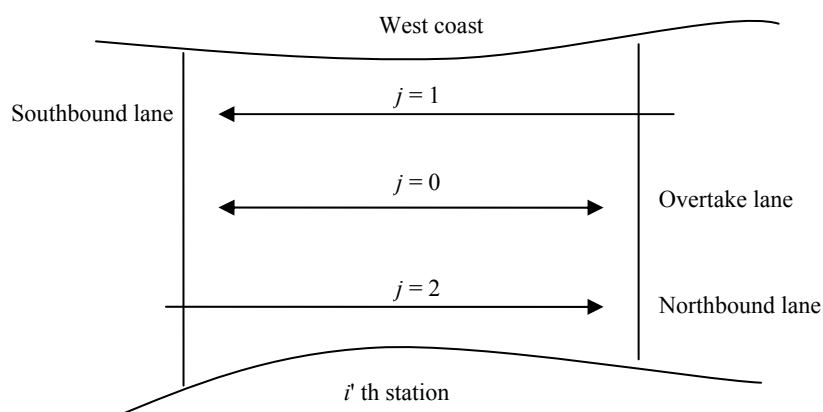


Figure 3.23. Representation of a station slice

Consequently, the current magnitude at day t for each station can be calculated through (3.11) in which $C_{i,j,t}$ is the current magnitude for the station ($i = 1, \dots, 21$) and for the lane $j = 0, 1, 2$; v_i is the vertical rate at station i ; h_j is the horizontal rate at lane j and A_t is the generated base current magnitude at day t .

$$C_{i,j,t} = v_i * h_j * A_t \quad (3.11)$$

3.3.2. The Autoregressive Base Current Model

The current magnitudes at Üsküdar station of VTS for a six month period are given in Figure 3.24.

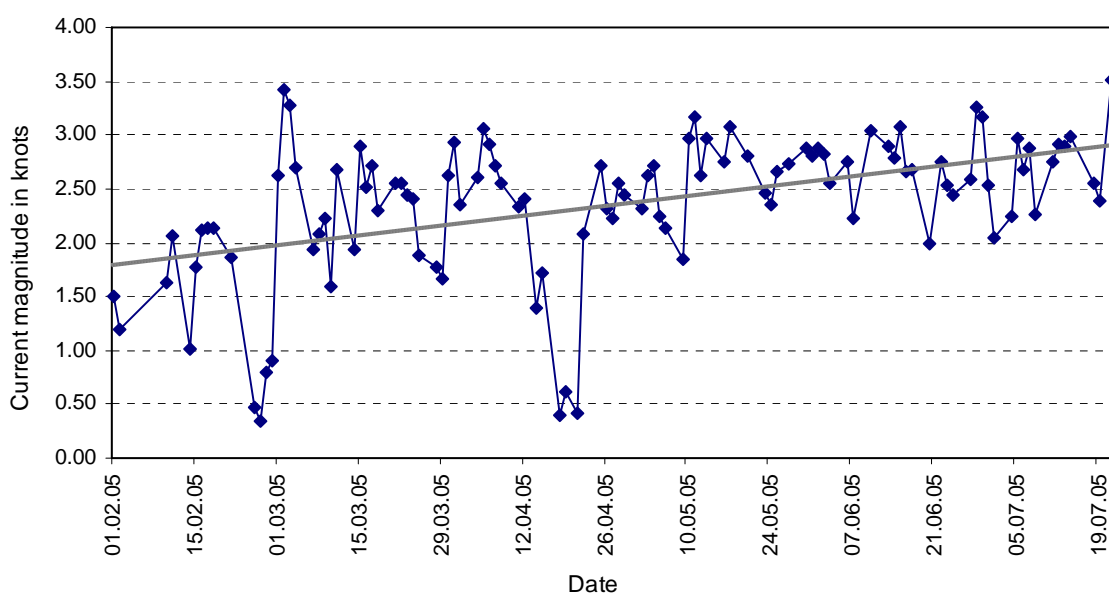


Figure 3.24. Current magnitudes at Üsküdar station

As can be seen from this figure, the current magnitudes show a slightly increasing trend when approaching the summer season. However, expert opinion did not confirm this increasing trend while there is no information available for other seasons/years. Thus, it is assumed that current behavior is stationary throughout the year.

The Üsküdar data is analyzed through Minitab statistical software for an appropriate fit to a model to generate daily current magnitudes for the Üsküdar station.

First, the data is checked for autocorrelations. The autocorrelation function (ACF) with 95 per cent confidence limits is given in Figure 3.25. The ACF for the Üsküdar data shows two significant large positive spikes at lag 1 and lag 2. All of the other autocorrelations are within 95 per cent confidence limits. The declining values of ACF are typical for autoregressive processes (Box et al., 1994).

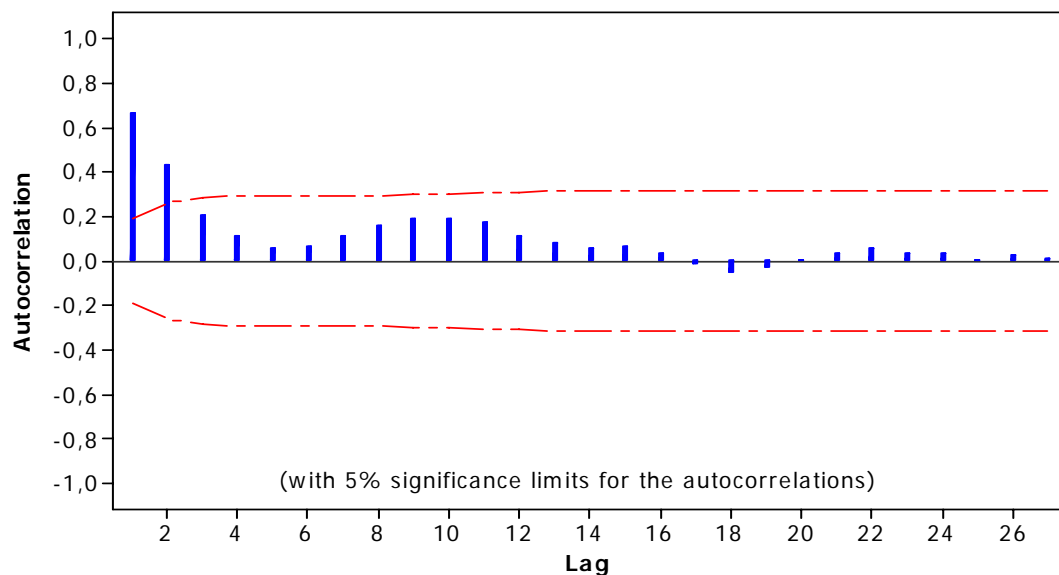


Figure 3.25. Autocorrelation function for Üsküdar data

To identify the appropriate process, the partial autocorrelation function should also be checked. The partial autocorrelation function (PACF) with 95 per cent confidence limits is given in Figure 3.26. The PACF for the Üsküdar data shows a large positive significant spike at lag 1. All other partial autocorrelations are within 95 per cent confidence limits. This pattern is typical to an autoregressive (AR) process and the number of significant spikes indicates the order of autoregression. In this case, although there are two significant

spikes in ACF, there is one significant spike in PACF, thus the order of the autoregressive process is one (Box et al., 1994).

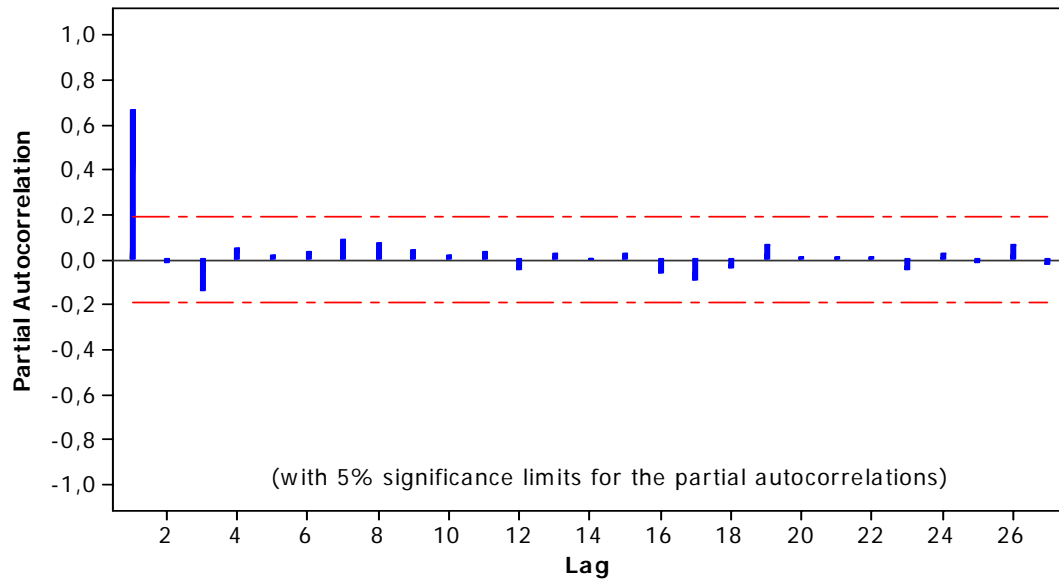


Figure 3.26. Partial autocorrelation function for Üsküdar data

In an autoregressive (AR) process, each value in a series is a linear function of the preceding value or values. In a first-order autoregressive process, only the single preceding value is used. That is, in an AR(1) process, the current value is a function of the preceding value, which is a function of the one preceding it, and so on. Thus, each shock or disturbance to the system has a diminishing effect on all subsequent time periods.

Table 3.17. Autoregressive AR(1) model for Üsküdar data

Type	Coef	SE Coef	T	P	SS	MS	df
AR(1)	0.6758	0.0717	9.43	0.000			
Constant	0.7617	0.0476	16.02	0.000			
Mean	2.3499	0.1467					
Residuals					25.8862	0.2442	106

The AR(1) function to be integrated in the simulation model to generate daily base current values for the Strait is given in (3.12). In this equation A_t is the current magnitude in day t , $A_0 = 2.3499$ is the initial current magnitude (which is the mean of the current data) and ε_t 's are independent and identically distributed (IID) normal random variables (since the residuals fit to normal probability plot in Figure 3.29) with mean 0 and variance chosen

to control $\text{Var}(A_t)$ (which is $MS = 0.2442$, the variance of residuals from Table 3.17) that makes $\varepsilon_t = N(0, 0.494)$.

$$A_t = (0.6758 * A_{t-1}) + (0.76177) + \varepsilon_t \quad (3.12)$$

Thus, function (3.12) generates a daily current value, depending on the previous day about 68 per cent (which is the correlation coefficient at lag one) and the rest of the current magnitude comes from random effects.

In order to confirm the identification of AR(1) process, the ACF and the PACF of the residuals should also be checked. The ACF of the residuals is given in Figure 3.27 and the PACF of the residuals is given in Figure 3.28.

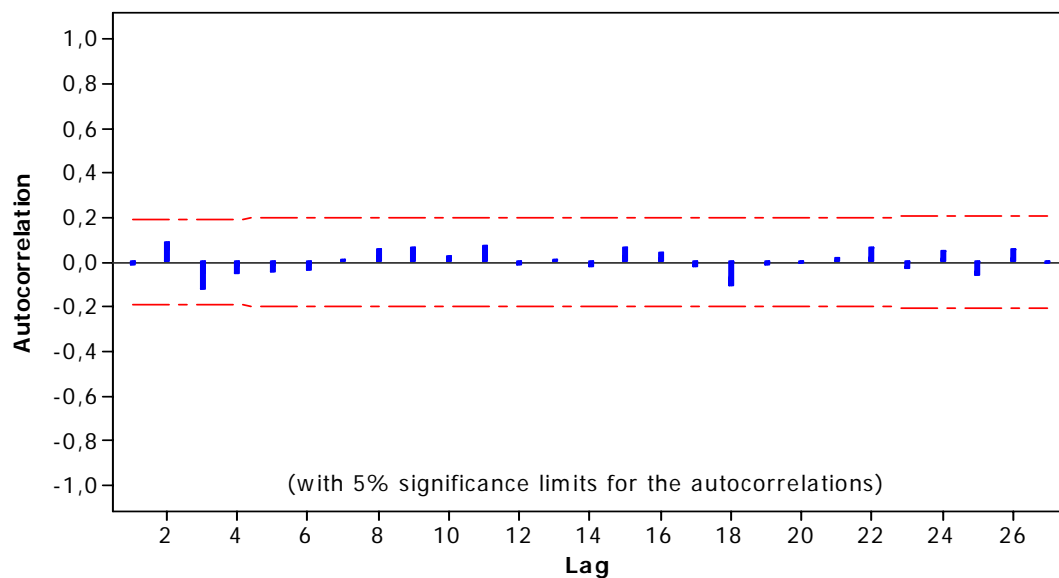


Figure 3.27. Autocorrelation function of residuals for the AR(1) model

The ACF and the PACF of the residuals show non significant spikes indicating that the residuals seem to be uncorrelated. Therefore, the AR(1) model seems to fit well to generate daily current values.

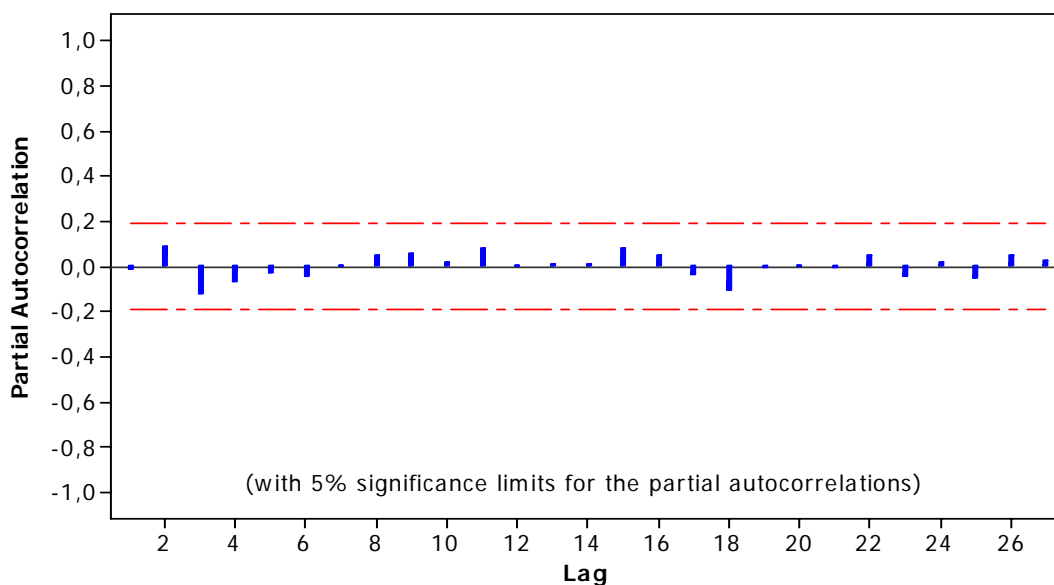


Figure 3.28. Partial autocorrelation function of residuals for the AR(1) model

To further check the assumptions of the autoregressive current submodel, residual plots are depicted in Figure 3.29. According to this figure, normality and constant variance assumptions seems to be satisfied with a few outliers.

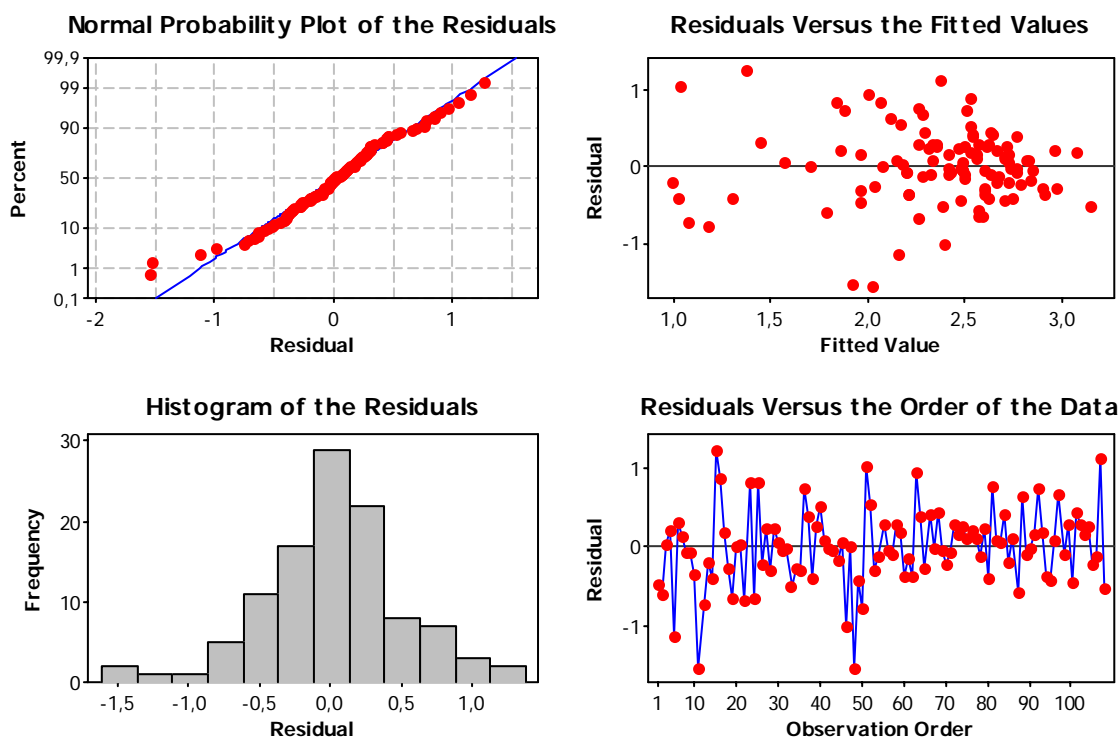


Figure 3.29. Residual plots for Üsküdar data AR(1) model

4. THE ISTANBUL STRAIT TRAFFIC SIMULATION MODEL

The simulation model of the transit traffic in the Strait of Istanbul is based on the Maritime Traffic Regulations for the Turkish Straits and the Application Instructions. The model is specifically designed to keep track of arriving vessels individually and resources in service, to gather and collect expressive statistics on waiting and transition processes of vessels in the Strait. Thus, various experiences of the 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 possibilities, current effects and pursuit distances are all incorporated in the simulation model. The model is developed through the Arena 9.0 simulation software.

A typical viewscreen of the simulation model is displayed in Figure 4.1.

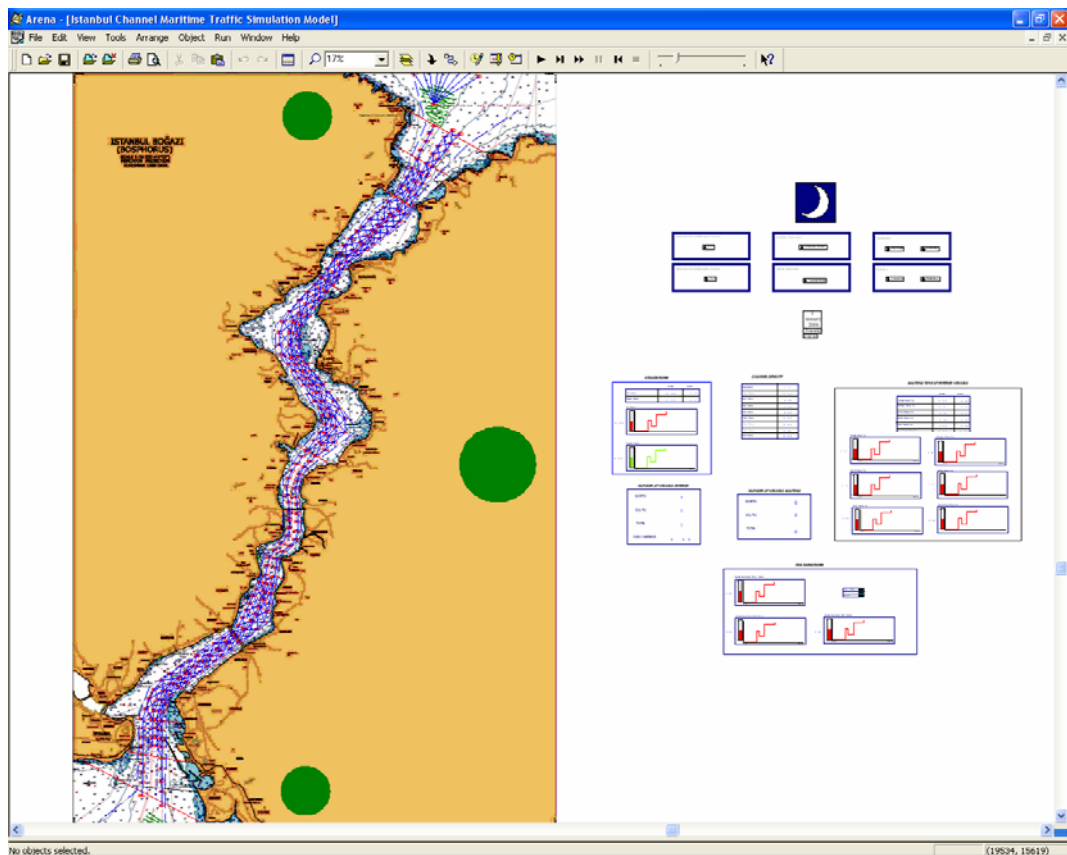


Figure 4.1. The Istanbul Strait Traffic Simulation Model

4.1. Vessel Classes

Vessel types considered in the simulation model are Passenger Vessels, LNG - LPG Carrying Vessels, Hazardous Material Carrying Vessels (HazMat), Tankers and General Cargo Carrying Vessels. On the other hand, the Strait Regulations classify all vessels into 11 treatment classes, based on their types, lengths and drafts, in a way reflecting the vessels' navigational complexity, potential risk, special needs and the associated transition rules and restrictions. These classes, which are displayed in Table 4.1, are also deployed in the simulation model, and the Strait entrance criteria are developed through these vessel classes.

Table 4.1. Vessel treatment classes

Length (meter)	Draft (meter)	Type				
		Tanker	LNG-LPG	HazMat	Gen Cargo	Passenger
< 50	< 15	T1	L2		G2	PA
50 - 100	< 15	T2	L3		G3	
100 - 150	< 15	T3	T4			
150 - 200	< 15	T5				
200 - 250	< 15	T6				
250 - 300	> 15	T6				
> 300	> 15	T6				

Figure 4.2 represents a schema for the transit vessel Rules adopted in the simulation model. The schema describes the basic rules for all of the treatment classes except T6 class (since T6 class vessels have at least the same conditions with T5 vessels, while further special transit conditions may be enforced upon them by the Strait Authority).

Any vessel desiring to enter the Strait first checks if its entry is restricted by other vessels which are already in the Strait (due to the rules summarized in Figure 4.2). Similarly, if the vessel is permitted to enter the Strait, it then restricts the entrance to the Strait of other relevant vessels due to the same set of rules. The “Kandilli Rule” of the schema displayed in Figure 4.2 deserves further explanation: According to this rule, the indicated vessel classes are not allowed to encounter one another in the Kanlıca – Vaniköy region (of the Strait) when traveling at opposite directions.

On the other hand, the block arrows near the borders of Fil Burnu and Boğaziçi Bridge in Figure 4.2 denote that other vessels having the same block arrows are not

permitted to be present in the intended region (i.e. Fil Burnu to Boğaziçi Bridge) when traveling in the same direction.

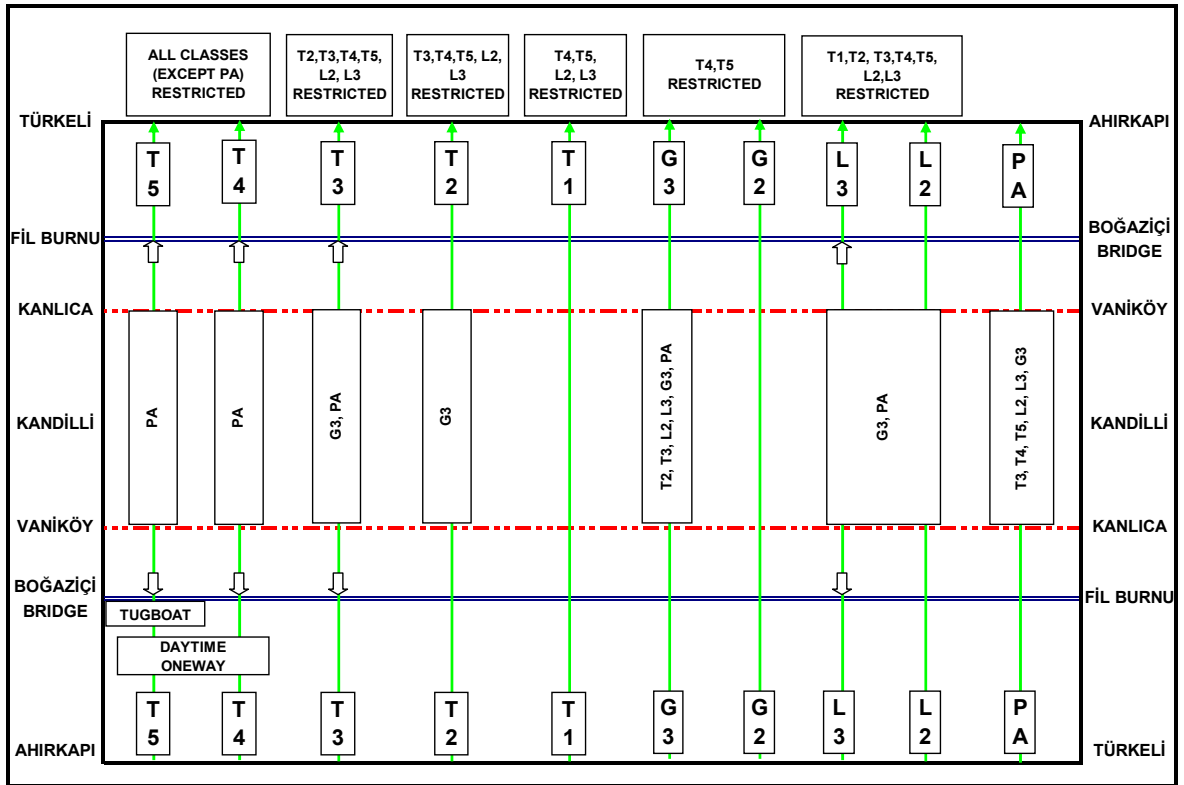


Figure 4.2. Strait of Istanbul transit vessel rules adopted in the simulation model

Lastly, T5 class vessels are required to have tugboats accompanying them throughout their Strait transit, while T4 and T5 class vessels are allowed to enter the Strait only in daytime.

4.2. The Strait Entrance

The arrival process to the Strait initiates with the generation of a series of individual transit vessels in one of the following two manners:

i) Interarrival times of various vessel clusters (with respect to type, length and direction) are assumed to be randomly distributed with respect to time invariant probability distributions. First, these probability distributions are estimated based on the actual transit vessel arrivals data of the year 2005 (i.e. approximately 50,000 vessel arrivals in total,

which is displayed in Table 3.1). In the estimation process Input Analyzer is deployed and the resulting set of vessel clusters and probability distributions (together with the statistics showing the soundness and validity of the estimation) are displayed in Table A.1 and Table A.3. Then, the random number generator of Arena is deployed to generate interarrival times for each vessel cluster according to the accepted probability distributions. Then, the generated vessels are assigned their remaining physical characteristics (such as lengths, traveling directions, direct / indirect status, anchoring duration if any, pilot needs and sailing speeds) according to the realized frequency of such characteristics of the actual vessels in that vessels cluster in the 2005 data. Finally, all generated vessel arrivals are ordered with respect to their associated arrival times (at one of the two Strait entrances).

ii) External inputting of a series of transit vessels based on their traveling direction, with the following characteristics preassigned to each vessel;

- Arrival time,
- Vessel type,
- Vessel length,
- Direct / indirect status,
- Anchoring duration,
- Pilot request,
- Speed.

In the 2005 data, there is no information on tugboat demand thus, both in internal generation and external inputting of data, a probability distribution based on the length class of vessels is assumed.

The (randomly) arrived vessels first enter the anchoring area according to their request and stay there through their anchoring durations (Table 3.5). Those who do not anchor or leave anchoring area are ready to enter the Strait.

For those vessels that have completed their local needs and anchoring time, ‘Ready Time’ and ‘Threshold’ attributes are assigned. Ready Time is the vessel attribute which is used to determine its ordering in the waiting queue and to calculate the waiting time in

queues. Threshold attribute is specifically used to determine the vessel's priority (in the sense that the Traffic Control Authority puts a 'Barrier' to the opposite Strait entrance, once a vessel has waited an amount of time defined by its threshold value). Similar to Özbaş (2005), 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. Those vessels are represented in Figure 4.2 as the restricted vessels. 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 if there are no vessels in transit in the Strait, whose presence hinders its entrance.

Similar to Özbaş (2005), the 'Common Queue' is designed to hold the already arrived, ready and waiting vessels and to check if the Strait is available and safe for their transit. Entrance to the Strait is repeatedly checked against the Rules and Regulations. By the term "repeatedly" it is meant that a new check is realized whenever a condition (such as location of a vessel in transit, busy / idle condition of a pilot / tugboat occurrence or termination of fog, change in current conditions, change in daytime / nighttime status) changes in the Strait. The ranking order of this queue is according to the least value of the 'Ready Time' attribute.

Each vessel in the 'Common Queue' checks for the satisfaction of the Strait Traffic Rules with respect to the existing traffic in the Strait. When there is no restriction due to the Rules, other factors such as pilot and tugboat needs, visibility, current level and daytime restrictions are checked with respect to that vessels needs and requirements. If all factors are suitable and the necessary services are available, then the vessel enters the Strait. This process is sequentially followed for all vessels in the 'Common Queue'.

4.3. The Pilotage and Tugboat Services

Pilot captain and tugboat usage in the Strait of Istanbul is strongly recommended by the Strait Authority to ensure safe navigation in the Strait. Thus, pilot captain and tugboat services are considered in the model. Pilot captains and tugboats are defined as limited resources, whose administration is a key issue both in real life and in the simulation model.

There are 15 pilot captains and six tugboats in service in the base scenario of the simulation model (this is also the current real situation).

Pilot embarking / disembarking stations are specified in the model and a certain amount of time is appointed to cover the slowing down and speeding up of vessels while executing the embarking or disembarking activity. Besides, when a pilot is seized, a service boat is also seized, since service boats are used to disembark or embark pilots.

Again, similar to Özbaş (2005), two control mechanisms have been added to the model to increase the utilizations of pilots and tugboats. At any entrance, while the pilot or tugboat is released, if the number of idle pilots or tugboats at that station is higher than or equal to a predefined limit, the excess pilots or tugboats are transferred to the opposite side station in 30 minutes and 90 minutes respectively (time allowed for deadheading). This limit parameter is determined as three for pilots and three for tugboats and kept unchanged throughout this study. Also, when a pilot or tugboat is seized by a vessel, number of remaining resources in that station is checked. If the value is zero and the station on the opposite side has more than two idle of that resource, the excess are sent to the side in need of. During the transfer of excess pilots and tugboats, number of transferring resources is also checked by a control mechanism, in order to avoid simultaneous transfers. When a vessel is just about to complete its Strait transit, it releases the pilot or tugboat assigned to it at the disembarking station. When the seized pilot or tugboat is released, it is designated to be an available resource at the released station.

4.4. The Strait

In the Strait, a vessel passes through eight different zones (Figure 4.3). This separation form is adopted from Kahraman (2001) to allow for a coherence between the studies. Each zone is divided into a sequence of ‘stations’, which are set at a distance of eight cables (0.8 nautical miles \approx 1.482 km.) from one another. Also, each station is comprised of four ‘substations’, which are two cables distance from one another (Table 4.2). This structure is designed to satisfy the Regulation that vessels in transit in the Strait shall maintain a certain pursuit distance between each other.



Figure 4.3. The Strait of Istanbul divided into eight zones (Kahraman, 1999)

Table 4.2. Zone lengths and number of stations

Zone no	No of stations	No of substation	Length (nautical miles)
1	2	8	1.6
2	3	12	2.4
3	2	8	1.6
4	3	12	2.4
5	4	16	3.2
6	5	20	4
7	1	4	0.8
8	1	4	0.8

The pursuit distance is actually a control parameter of the Traffic Control Authority and is also deployed as such in the model. According to a strict interpretation of the Regulations, this pursuit distance is eight cables, but the controllers at the Strait Authority have the power and responsibility to reduce the pursuit distance considerably if they see it fit. Thus, the pursuit distance is also parameterized in the model (through the definition of substations at a distance of two cables from one another) such that it is determined at the beginning of a simulation run and can take values of two, four, six, eight or ten cables distances.

The Strait is represented on 21 stations or 84 substations to cover a distance of 16.8 nautical miles. The pilot embarking / disembarking stations are situated after the 16th substation from the North entrance and after the 8th substation from the South entrance. The traffic lanes are arranged according to the Traffic Separation Scheme (TSS) defined by Strait Regulations as well.

Each substation in the simulation model is comprised of several elements defined and blocks of Arena to mimic the transition of each vessel throughout the Strait. A substation is established by a station block (to define the present position of a vessel), a resource (to seize the position), an assign block (to perform required current effect, speed, position and transition calculations), a check algorithm built by branch and scan blocks (to decide a transition and a route block to realize a two cables progress in the Strait). All stations, resources and position information are defined on numerals and on arrays to handle the complexity of calculations.

Accordingly, the movement of individual vessels in the Strait is achieved by moving each vessel to the neighboring substation in the intended direction, after a certain amount of time passage (with respect to vessel speed and station separation) if that neighboring station is idle (i.e. not occupied by another vessel). Throughout these movements of vessels in the Strait, any condition change is also followed by signal blocks or scan blocks for those vessels who are waiting in the ‘Common Queue’ and checking for the suitable conditions to enter the Strait. In addition, following entrance to and exit from the Strait, various statistical information on the vessels are collected.

4.5. Overtaking

The simulation model provides three traffic lanes (along the Strait) for transit vessels. One southbound lane, one northbound lane and an additional lane for overtaking, wherever it is allowed, are built in the model. In line with the Strait Regulations, the overtaking lane is removed from the model at the Kandilli region (between Vaniköy and Kanlıca points), which is the narrowest region of the Strait.

The article 14 of Maritime Traffic Regulations for the Turkish Straits and the Marmara Region (1998) states on overtaking that,

“Vessels navigating in the Straits shall not overtake vessels proceeding before them except due to necessity.

...

(d) When a vessel needs to overtake another in front of it proceeding at a lower speed, it shall first obtain a traffic report from the traffic control station, and if the situation is clear, shall inform the vessel to be overtaken. The overtaking shall if possible take place without course alterations.

(e) Overtaking will not take place between Vaniköy and Kanlıca in the Strait of Istanbul...”

The overtaking rules implemented in the model takes the above mentioned article into consideration. The density of nearby traffic, sufficient room, collision risk and success of overtaking factors are tried to be formulized. Thus, whenever a vessel is faster than the one ahead, it checks three conditions,

- (i) If it is fast enough to complete the attempted overtaking before it reaches the Kandilli region or the Strait exit (at which no further overtaking action is permitted),
- (ii) If the closest vessel in the overtaking lane traveling in the same direction and the closest approaching vessel in the opposite lane is at least “the safe distance” or “the pursuit distance” away,
- (iii) If no vessel from the opposite direction is occupying the section of the overtaking lane to be deployed in the overtake.

In cases where the above conditions are not satisfied, vessels are not allowed to overtake the vessels in front. Consequently, whenever overtaking is not possible, a vessel proceeds in the Strait with speed of the vessel in front even if it is faster than the vessel ahead.

The above condition (i) is formalized in the model as follows. Let p be the pursuit distance (as substations between vessels), v_i be the average speed of vessel i for $i = 1, 2$ (with respect to land) and $k = 0.2$ nautical miles be the distance between substations. Then, according to (4.1) Δt is the time to complete an overtake and S is the total number of substations to be passed during the attempted overtake.

$$\Delta t = \frac{p * k}{v_2 - v_1} \quad , \quad S = \frac{v_2 * \Delta t}{k} \quad (4.1)$$

In order to satisfy the overtaking condition (i), the total number of substations to be passed (S) should be less than the number of remaining substations (R) up to the expected completion point of overtaking. Then, using equations (4.1), the relevant condition would be the equation (4.2).

$$\frac{v_2 * p}{v_2 - v_1} \leq R \quad (4.2)$$

The vessel speeds in equation (4.2) also includes average current speeds since vessels will be exposed to different current values at each station of each lane. Thus, the speed of vessels and the speed difference between two vessels will change as the vessels move from one station to another. Besides, the current values in the overtaking lane and the main lanes are different in a station slice. Therefore, the average current speeds up to the Kandilli region are calculated for each station of each lane.

Equation (4.2) is the initial condition to satisfy in order to initiate an overtake. For those vessels that cannot satisfy (4.2), there is no need to check other conditions. The strictness and level of this condition is important in increasing the success of overtaking and reducing the fail rate (and thereby avoiding unnecessary overtaking attempts). It also

closely mimics the behavior and control actions of the Strait Authority regarding overtaking permissions. Overtaking attempts can be controlled in the model through “the pursuit distance” parameter as well.

4.6. The Visibility

The visibility submodel is developed through Arena 9.0 as an independent module and integrated to the simulation model of transit traffic in the Strait of Istanbul. The visibility submodel is based on the statistical analysis of historical data from different sources. The random generation of fog initiations in the summer and transition seasons are based on empirical distributions, whereas the winter season (based on an on / off process) is modeled through a phase type distribution. The duration of fog events (namely the off-period) is also modeled through phase type distributions.

On the other hand, due to the safety extension adopted by the Strait Authority, the duration of fog events are enlarged by 25 per cent before they are applied as closure durations. Then, the closure patterns and procedures of the Strait Authority under fog occurrences is represented through a decision flow, which is further calibrated based on the number of closes and closure duration rates in the past statistics.

According to the Strait Regulations and Application Instructions, the rules applied in the simulation model are given below.

- When visibility is less than one nautical mile in the Strait, only one-way traffic is permitted and dangerous cargo carrying vessels (Tanker, LNG-LPG, HazMat type vessels) and vessels longer than 200 meters are not allowed in the Strait.
- When visibility is less than 0.5 nautical miles in the Strait, all traffic is seized until more favorable visibility conditions.

The direction and level of closure (one-way or two-way) is determined through the closure decision flow (Figure 3.15) and controlled in the model through three binary variables of “Availability (i)” for $i = 0, 1, 2$, in which “0” indicates “two-way”, “1” indicates “southbound” and “2” indicates “northbound” traffic. These variables, which

facilitate the enforcement of the Strait Regulations, are controlled by the visibility submodel.

4.7. The Current

The current submodel is also developed through Arena 9.0 as an independent module within the simulation model of transit traffic in the Strait of Istanbul. An autoregressive function of order one generates a daily base current value in the Strait through equation (3.12) and local current values are then reflected to the stations in the Strait through equation (3.11) via predetermined percentage factors (of the generated base value), based on historical data for each station.

The main effect of the current is on the Strait entrance rules. The maximum current magnitude observed at any point of the Strait affects the permission of vessels to the Strait. Since the station at which the maximum current is realized is predetermined in the current model, that maximum value is calculated along with generation of the daily base current value.

The effect of maximum current on the Strait entrance rules of the model are based on the Strait Regulations and Application Instructions. The conditions are given below.

- If the current is less than 4 knots, vessels with speed less than four knots are restricted or appointed a tugboat for a safe passage through the Strait.
- If the current is more than 4 knots or orkoz occurs, i) vessels with speed less than four knots, ii) dangerous cargo carrying vessels (Tanker, LNG-LPG and HazMat type vessels) with speed less than 10 knots and iii) vessels longer than 200 meters with speed less than 10 knots, are restricted to enter the Strait.
- When the current is more than 6 knots or strong orkoz occurs, i) vessels with speed less than four knots, ii) dangerous cargo carrying vessels and iii) vessels longer than 200 meters, are restricted to enter the Strait until the current conditions change to safe levels.

The secondary effect of current is on vessel speeds. Since the Strait of Istanbul almost always features a north to south surface current, the current affects the realized speed of vessels through speeding up the southbound vessels and slowing down the northbound vessels. The speed alterations are affected by simply adding or subtracting the local current value (which is daily computed and assigned as described above) to or from the speed of the vessel passing through the related station.

Furthermore, the current speed also affects the overtaking conditions: since any attempted overtake must be completed by the Kandilli region and since local current value changes by station and by lane, average current values up to the Kandilli region for each substation and each lane are also calculated when daily current value is generated. The vessels use these average current values to compare their realized speeds with that of the vessel they aim to overtake, when checking the conditions for overtaking permissions.

Another usage of current speeds is in the calculation of the Kandilli region encounter prevention rule. In order to check and satisfy this rule, the Kandilli region entrance and exit times of vessels need to be compared. Therefore, to calculate an accurate estimate for the entrance and exit times of vessels to the Kandilli region, average current speeds for the three regions (before, after and inside the Kandilli region) are also calculated after the generation of daily current values.

4.8. The Seasons

The effect of seasons in the model is represented through the seasonality feature of the visibility submodel and through the implementation of different daytime and nighttime durations throughout the year.

As mentioned before, low visibility levels (which have a direct effect on all vessels) are more frequent during the winter season. In the simulation model, winter season comprises of months from November to April; summer season comprises of months from June to September and the transition season includes May and October. Each of these seasons has its own visibility distributions, which are discussed in section 3.2.

The length of daytime and nighttime has an effect due to the Strait Regulation's daytime restriction on the passage of T4 and T5 class vessels. The daytime lengths assumed which comprise of the difference of sunrise and sunset times according to months, are given in Table 4.3.

Table 4.3. Seasonal day length, sunrise and sunset times

	<i>Day length</i>	<i>Sunrise</i>	<i>Sunset</i>
<i>January</i>	10	07:00	17:00
<i>February</i>	11	07:00	18:00
<i>March</i>	12	07:00	19:00
<i>April</i>	13	06:00	19:00
<i>May</i>	14	06:00	20:00
<i>June</i>	15	06:00	21:00
<i>July</i>	16	05:00	21:00
<i>August</i>	15	06:00	21:00
<i>September</i>	14	06:00	20:00
<i>October</i>	13	06:00	19:00
<i>November</i>	12	07:00	19:00
<i>December</i>	11	07:00	18:00

4.9. The Animation

The simulation model developed also includes a real time animation of vessel movements through the Strait of Istanbul during a simulation run. The main functions of this animation are to communicate the essence of the simulation model and debugging of the simulation program. A viewscreen of the animation is displayed in Figure 4.4.



Figure 4.4. An viewscreen of the animation

4.10. Statistics Collection and Outputs Files

Each simulation run generates several output files for statistics collection, to keep track of variable changes and random variables generated in the model related to the transit vessels, fog occurrences and the current conditions. The statistics collection is monthly based and it is assumed that one month is 30 days and a year is 360 days to simplify statistics collection efforts and comparisons between simulation runs.

The major output file is associated with the collected statistics on transit vessels with respect to north and south entrances, total entrances for all vessels and for each vessel type. The statistical values include maximum, minimum, average values, standard deviations and 95 percent confidence intervals of the following output variables;

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

The other output files are used to keep track of fog occurrences and the Strait closures due to visibility, to record daily current magnitudes, to follow the Kandilli rule violations, to keep track of vessel transitions and overtaking attempts throughout the Strait and to follow the overtaking lane utilizations.

5. VERIFICATION, VALIDATION AND OUTPUT COMPARISONS

Verification is related to correct translation of a conceptual model into a simulation program. On the other hand validation is concerned with accurate representation of the real system through the simulation model.

There are two important goals in the validation process. The first one is to produce a model to represent the real system behavior close enough to be used for experimentation purposes. The second is to build a credible model to be used by managers and other decision makers (Banks et al., 2001).

A simulation model of a complex system can only be an approximation to the actual system. Thus, a model should always be developed for a particular set of purposes and a model that is valid for one purpose may not be for another. Accurate specification of simulation objectives is crucial for the success of the simulation study. The study objectives indicate how representative the model should be. Then, the model credibility must be judged with respect to the study objectives (Law and Kelton, 2000; Balçı, 1995).

As mentioned before, the objective of this study is to analyze the effectiveness of various policies and decisions related to the transit traffic in the Strait of Istanbul, as well as to investigate the effects and the interrelations of several factors affecting the system. In line with this objective, there are some assumptions and simplifications to facilitate the development and utilization of the simulation model. Thus, the simulation model does not aim to be totally representative of the overall system, but to take into account the major components to reflect the important facts and to test the effects of concerned factors on the system through scenario analysis.

5.1. The Verification of the Traffic Simulation Model

According to Balçı (1995), validation, verification and testing must be conducted through the life cycle of a simulation study as a continuous activity. The Strait of Istanbul

Maritime Traffic Simulation Model is developed in stages and each stage proceeded with discussions and controls on each item to be added to the model through a structured walk-through. Besides, since the simulation model is comprised of several components, such as the visibility submodel, the current submodel, the arrival process and the actual vessel movements, each is individually debugged and tested before integrated into one model.

One of the objectives of the simulation model is to keep track of every movement of vessels from arrival to departure. Thus, keeping records of vessel movements facilitated to identify errors and recognize model deficiencies for verification purposes. Similar to this, animation is also used to better understand and track the model behavior and to accomplish verification.

To check that the model is transformed from one form into another with sufficient accuracy, another sophisticated technique effectively used is tracing. A trace is a detailed computer output of a simulation run, which gives the value of every variable in the model as the simulation clock proceeds. Thus, any unexpected movement of an entity or a change in a variable can be detected. Trace feature was extensively used in the development phase to identify sources of errors in the model and for debugging.

The model is also run under some simplifying assumptions, to isolate specific issues and to better understand the model behavior. A basic test in this regard has been the generation of just one vessel for the North and the South entrances in turn, in order to observe the flow in trace. Furthermore, to compare the transition of northbound and southbound vessels, the current effects were closed and to compare waiting times of the North and the South entrances, the visibility effects were turned off. Another trial was performed with identical inputs for both the North and the South entrances simultaneously, in order to test the variation between the two flows. All those tests gave reasonable results and there was no indication of incorrect transformation of the conceptual model into the computerized model.

5.2. Validation and Output Comparisons

Face validity is an important issue for model users and others, who are knowledgeable about the real system being simulated. The outputs of the simulation model and the scenario analysis are evaluated and discussed with the Strait Authority experts in a workshop and the feedbacks obtained are found to be reasonable, according to the assumptions and simplifications of the model.

The data used for model inputs and for output comparisons are collected through authorized sources. The deficiencies in the data on relevant issues were tried to be reduced through expert opinion and through proofreading and classification in the analyses phases. Also, the probability distributions fitted to the data (especially the ones associated with the arrival processes) were further checked using graphical plots or goodness of fit tests, whenever possible.

The most definitive test of a simulation model's validity is establishing that its output data closely resemble the output data observed from the actual system under similar environmental conditions. Results validation is accomplished when the two sets of data compare closely. However, the accuracy required from the model will depend on its intended use and the utility function of the decision maker (Law, 2005).

As mentioned before, the Strait simulation model has many simplifying assumptions on the real system. Essentially, the Strait Regulations are applied in the simulation model, but the precise Strait entrance procedures and the specific directives of the controllers are not aimed to be represented. Furthermore, it is very difficult to model the instantaneous and in many cases subjective and instinct based decisions of the controllers and their interpretations of the Regulations. That is, Rule and Regulation relaxations or variations in their interpretations (which do occur in real life) are not possible during the simulation runs, but can be analyzed through parameter changes over multiple runs. Lastly, there are also some factors that are not included in the model, such as extreme weather conditions at the Black Sea, which has direct effect on the Strait entrance priorities and vessel arrival profile at the Strait. Consequently, the comparisons between the simulation outputs and the real system are basically concerned with the proximity of major output variables of the

model to the real system outputs and sufficiency of the model to capture the behavior and trends of the real system.

5.2.1. The Comparison of the Year 2005 Statistics and the Outputs of the Simulation Model with External Inputting Structure

In order to compare the real system and the simulation model, historical data can directly be used as input data. In this way, random effects in the input stream are eliminated and this provides a basic comparison of the essential model structures of the Strait entrance rules and vessel transitions in the Strait, to the real system.

There are two sets of historical data of the year 2005 to be used as input data to the model for a seven month period. One set is for the actual vessels arrivals at the Strait and the other set is for the actual Strait closure times due to visibility. The vessel arrivals data includes vessel arrival times, vessel types, lengths, speeds, anchoring durations and pilot demands. The closure of the Strait data includes Strait closing times due to visibility, Strait opening times and closed direction of traffic. Thus, in this stage of the validation process the randomized arrival process and the visibility submodel are not used but the historical data are directly read into the simulation model from text files. Apart from vessel arrivals and visibility conditions, the other inputs of the simulation such as daily current magnitude and tugboat demands are randomly generated through the estimated probability distributions (as explained in section 3.1 and 3.3), since historical input data on these inputs could not be obtained.

The historical data on closures of the Strait due to visibility conditions, for the first seven months of 2005, which are used as input to the simulation model, are given in Table 5.1 and Figure 5.1.

Table 5.1. The actual Strait closure durations for the seven months of 2005

<i>Month</i>	<i>Two-way</i>	<i>Southbound</i>	<i>Northbound</i>	<i>Total</i>
1	82:30	1:05	5:13	88:48
2	63:42	11:31	32:25	107:38
3	80:47	1:03	4:05	85:55
4	12:40	0:00	0:00	12:40
5	38:09	0:00	0:50	38:59
6	0:45	0:00	0:00	0:45
7	3:05	3:15	0:00	6:20
<i>Total</i>	281:38	16:54	42:33	341:05

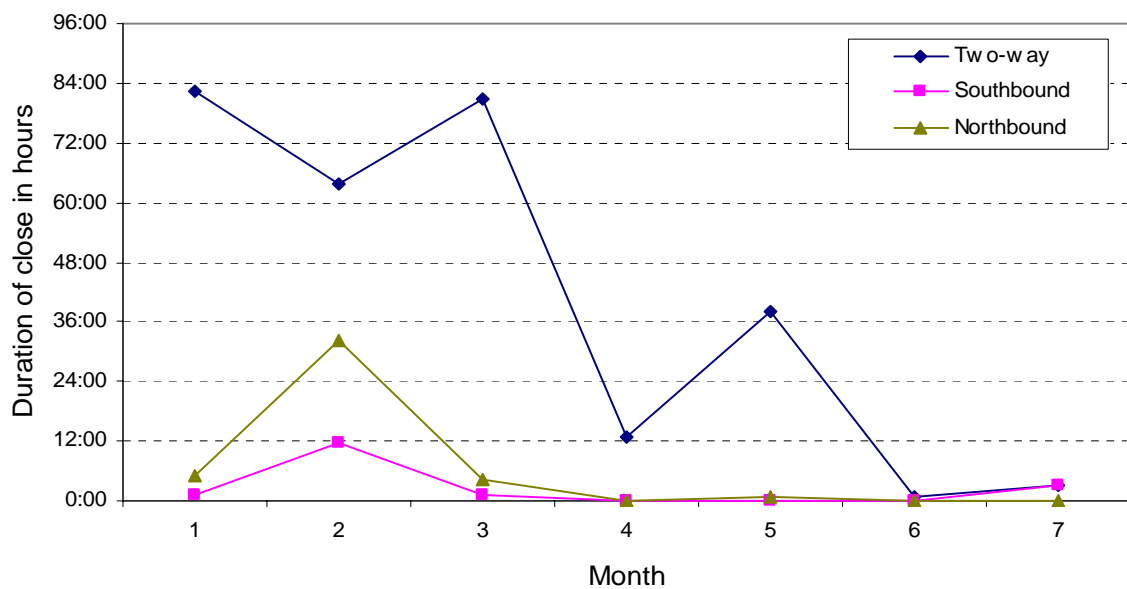


Figure 5.1. The actual Strait closure durations in the first seven months of 2005

Then, the simulation model is run for the indicated seven month period with 10 replications, in order to compare the results to the statistics of 2005. Additionally, a one month warm-up period (December) was deployed to reach a steady-state (statistics for this month are excluded). The input data for this warm-up period is also selected from the real input data in order to better represent the conditions for December. The basic performance measures to compare are the number of vessels passed, the average transit time and the average waiting time of vessels. The vessel density in the Strait, the number of vessels in queues, pilot and tugboat utilizations are also presented, but could not be compared due to lack of relevant historical data.

In order to evaluate the difference between the performance measures of the system and the simulation model, lower and upper confidence levels are also presented. The confidence intervals based on t -distribution (even if sample size is too small) are wider than the confidence intervals based on normal distributions and generally have coverage closer to the desired level of $(1- \alpha)$. Thus, the 99 per cent confidence levels for the simulation outputs are calculated through the t -confidence interval.

The actual total number of vessels passed in the first seven months of 2005 and the mean of the total number of vessels passed in 10 replication simulation runs are given in Table 5.2. Also, the distribution of total vessels passed in seven months period is given in Figure 5.2. The total, southbound and northbound vessel numbers passed in real data and in simulation results are very close. Besides, the distribution of the total number of vessels passed in the seven months period simulation outputs are in accordance with the 2005 data outputs. The slight differences in the first and the fourth months between the simulation results and the actual data are arguably due to various reasons. Especially the input data of the warm-up period (December) are not actual and could affect the following months. Besides, it should be taken into consideration that specific directives and instinct based decisions of the controllers at any time could cause this kind of differences.

Table 5.2. The number of vessels passed in the first seven months in the actual 2005 data and in the simulation runs of 10 replications with external inputting structure

<i>Direction</i>	<i>The 2005 Data</i>	<i>The Simulation Model</i>			
	<i>Total</i>	<i>Mean</i>	<i>Standard deviation</i>	<i>Lower confidence</i>	<i>Upper confidence</i>
<i>Total</i>	31411	31468	22	31446	31491
<i>NS</i>	15712	15738	21	15717	15759
<i>SN</i>	15699	15731	7	15724	15737

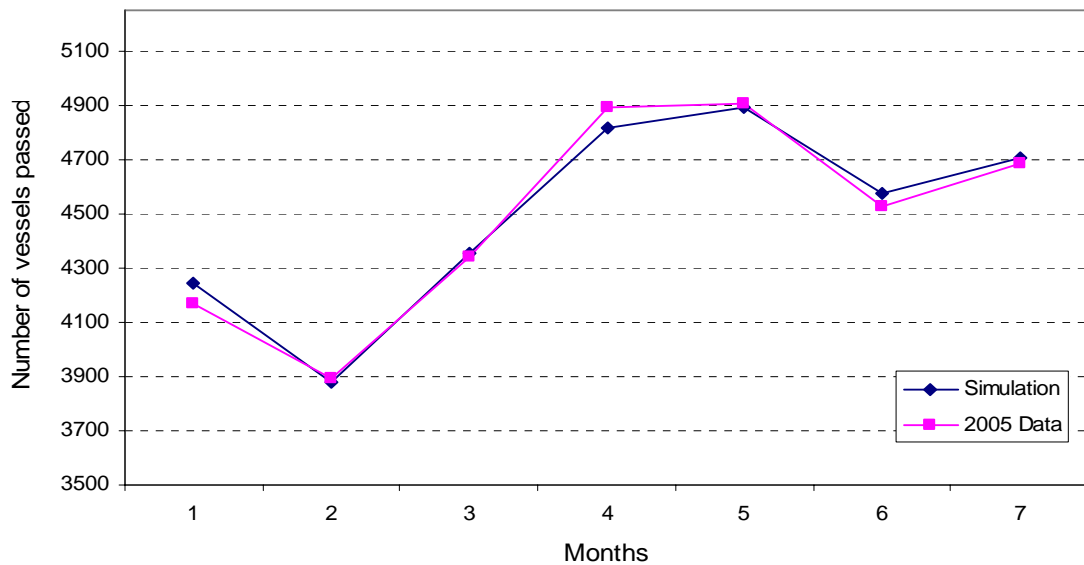


Figure 5.2. The distribution of total number of vessels passed in the first seven months of 2005 and in the simulation runs of 10 replication with external inputting structure

The mean and standard deviation of transit times of vessels both in the 2005 data and in the 10 replication simulation runs are given in Table 5.3 and in Table 5.4. As can be seen from these tables, the mean transit times of total, southbound and northbound vessels (for the simulation runs versus the actual situation) do not differ too much and are very close to the upper confidence limits; standard deviations on the other hand differ slightly.

Table 5.3. The average transit times in the actual 2005 data and in the simulation runs of 10 replications with external inputting structure

Direction	The 2005 Data	The Simulation Model			
	Mean (minutes)	Mean (minutes)	Standard deviation	Lower confidence	Upper confidence
Total	103.26	102.79	0.22	102.56	103.01
NS	93.26	93.00	0.21	92.79	93.20
SN	113.31	112.58	0.58	111.99	113.16

Table 5.4. The standard deviation of transit times in the actual 2005 data and in the simulation runs of 10 replications with external inputting structure

Direction	The 2005 Data	The Simulation Model			
	Mean (minutes)	Mean	Standard deviation	Lower confidence	Upper confidence
Total	21.59	18.23	0.32	17.91	18.55
NS	13.65	11.51	0.18	11.33	11.69
SN	23.36	18.44	0.26	18.18	18.70

The average waiting times of total, southbound and northbound vessels in the mentioned seven months are given in Figure 5.3, Figure 5.4 and Figure 5.5 respectively. As can be seen from these figures, the average waiting times of total vessels in simulation runs of 10 replications are significantly lower than the real data in the first three months; however, the realizations of the last four months are represented well by the simulation results.

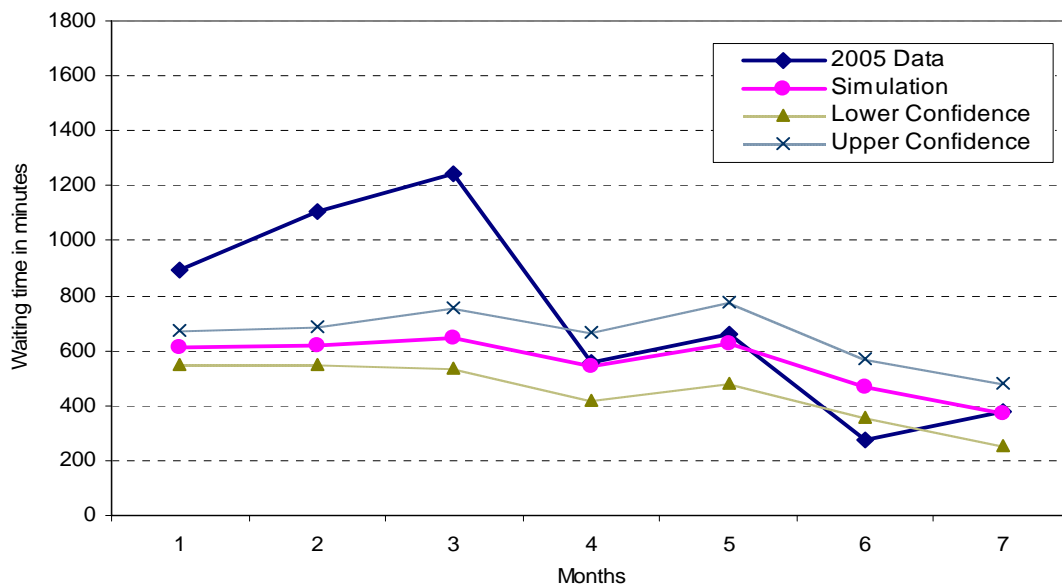


Figure 5.3. The average waiting time of total vessels in the actual 2005 data and in the simulation runs of 10 replications with external inputting structure (January - July)

The details of the difference in the first three months can be better seen through southbound and northbound vessels' waiting times in Figure 5.4 and Figure 5.5. The waiting times of southbound vessels of the simulation runs are close to that of the real data. On the other hand, waiting times of northbound vessels in the 2005 data are very high for the first three months (at around 1200 minutes and 1700 minutes) whereas simulation results are around 700 minutes.

One probable reason of the high waiting times of northbound vessels in the first three months is due to the bad weather conditions at the Black Sea. As mentioned before, in reality, extreme meteorological conditions, like major storms in the Black Sea, has direct affect on the vessel transitions at the Strait. At such emergency situations, the Strait Authority favors the vessels waiting at the North entrance of the Strait and further delays

those at the southern entrance. The modeling of these extreme meteorological conditions kept out of scope for this study (however, although these situations can not be affected during a single simulation run, they can be analyzed through multiple runs in scenario analysis).

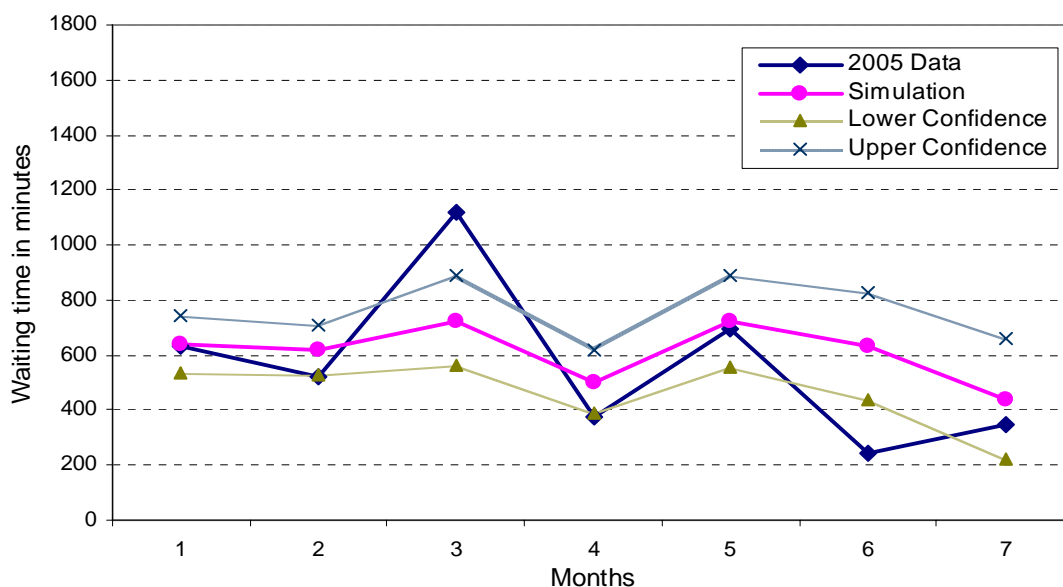


Figure 5.4. The average waiting time of southbound vessels in the actual 2005 data and in the simulation runs of 10 replications with external inputting structure (January - July)

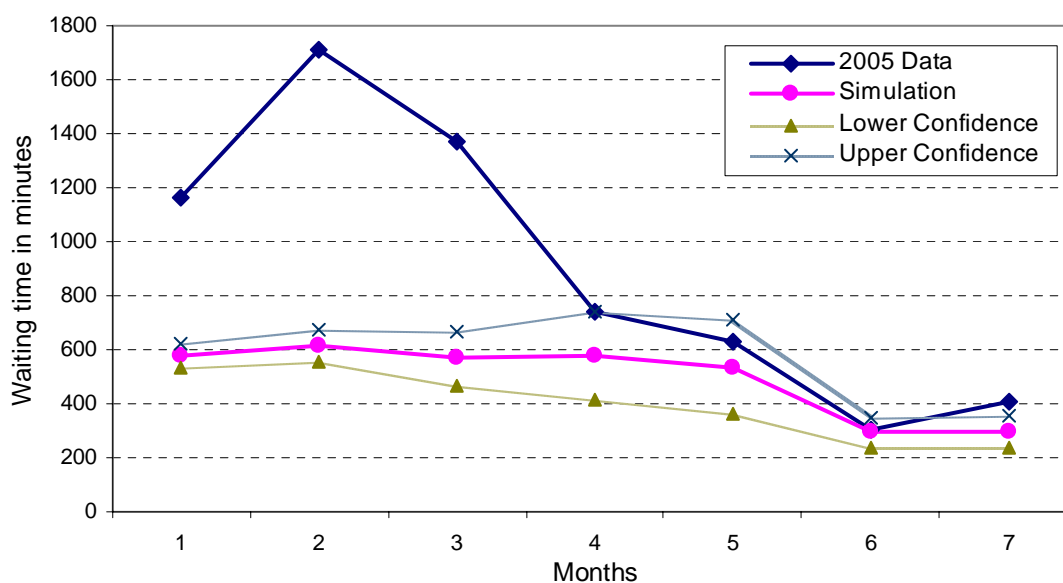


Figure 5.5. The average waiting time of northbound vessels in the actual 2005 data and in the simulation runs of 10 replications with external inputting structure (January - July)

The averages and standard deviations of waiting times, in the last four months of the actual 2005 data and in the 10 replication simulation runs are given in Table 5.5 and in Table 5.6 respectively (due to the explanation provided above, only the relevant figures of the last four months are considered). As can be seen from these tables, the average waiting times for the total, southbound and northbound vessels (of the simulation runs and of the real data) are very close. However, the standard deviations are lower in the real data than it is in the simulation model.

Table 5.5. The average waiting times in the last four months of the 2005 data and in the simulation runs of 10 replications with external inputting structure

<i>Direction</i>	<i>The 2005 Data</i>	<i>The Simulation Model</i>			
	<i>Mean (minutes)</i>	<i>Mean (minutes)</i>	<i>Standard deviation</i>	<i>Lower confidence</i>	<i>Upper confidence</i>
<i>Total</i>	470.53	501.81	66.08	435.59	568.03
<i>NS</i>	417.99	574.64	111.84	462.55	686.73
<i>SN</i>	522.82	429.25	73.65	355.44	503.06

Table 5.6. The standard deviation of waiting times in the last four months of the 2005 data and in the simulation runs of 10 replications with external inputting structure

<i>Direction</i>	<i>The 2005 Data</i>	<i>The Simulation Model</i>			
	<i>Mean (minutes)</i>	<i>Mean</i>	<i>Standard deviation</i>	<i>Lower confidence</i>	<i>Upper confidence</i>
<i>Total</i>	508.03	987.57	228.14	758.93	1216.22
<i>NS</i>	482.80	1031.35	236.72	794.11	1268.59
<i>SN</i>	526.81	923.72	255.25	667.91	1179.53

The cumulative average of the number of vessels in the queues in the mentioned seven months, as determined by the 10 replication simulation runs, is depicted in Figure 5.6. The average is weighted to take into consideration the queue length as a function of time. (Unfortunately, there is no information in real data to compare this output.) As can be seen from this figure, the average queue length is between 40 and 50 throughout the seven months. Nevertheless, value of queue length seems reasonable for the system.

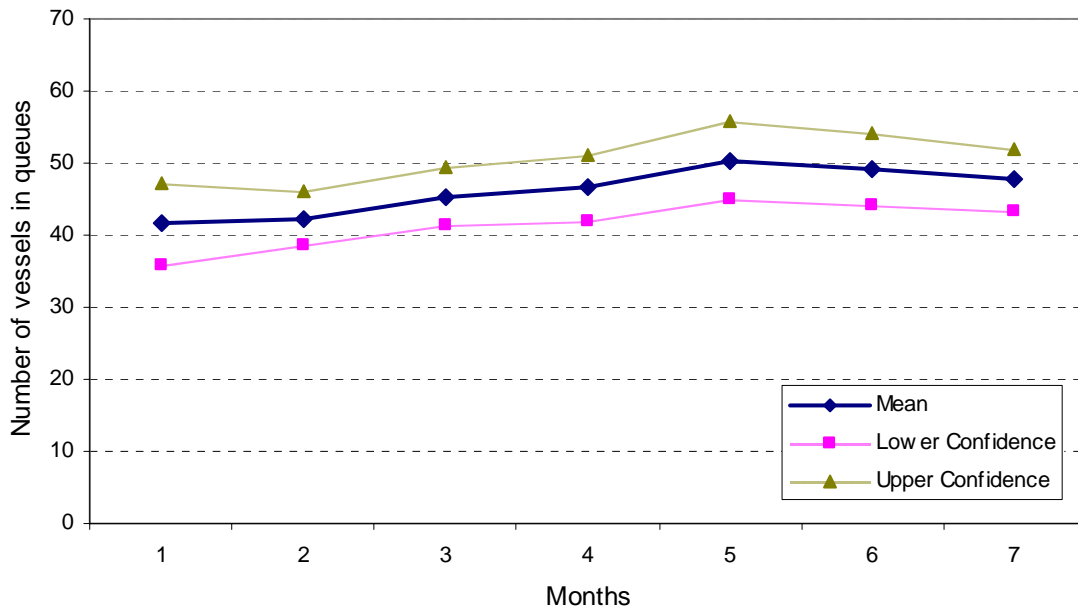


Figure 5.6. The cumulative average number of vessels in the queues in the simulation runs of 10 replications with external inputting structure (January - July)

The vessel density and the average number of vessels in the Strait, as determined by the 10 replication simulation runs, are displayed in Table 5.7. These statistics (which are weighted with respect to time) indicate that on the average there are about 11 vessels in the Strait at any given time. Although there is no real data to compare this statistic with, it seems very reasonable.

Table 5.7. The vessel density and the average number of vessels in the Strait in the simulation runs of 10 replications with external inputting structure

	<i>Mean</i>	<i>Standard deviation</i>	<i>Lower confidence</i>	<i>Upper confidence</i>
<i>Vessel density per nautical mile in the Strait</i>	0.637	0.0014	0.635	0.638
<i>Average number of vessels in the Strait</i>	10.699	0.0238	10.675	10.722

The pilot and tugboat utilizations in the Strait, as determined by the 10 replication simulation runs, are given in Table 5.8. These values are again weighted with respect to time. As can be seen from this table, the average number of pilots in use at any time is expected to be 4.5 of the available 15 pilots and the average number of tugboats in use at any time is expected to be 3 of the 6 tugboats. Although there is no related real data to

compare with, these values seem reasonable, taking into consideration the pilot and tugboat demands and the expected number of vessels in the Strait.

Table 5.8. The pilot and the tugboat utilizations in the simulation runs of 10 replications with external inputting structure

	<i>Mean</i>	<i>Standard deviation</i>	<i>Lower confidence</i>	<i>Upper confidence</i>
<i>Pilot Utilization</i>	0.3005	0.0008	0.2997	0.3013
<i>Average number of pilots in use</i>	4.51	0.01	4.49	4.52
<i>Tugboat Utilization</i>	0.5054	0.0031	0.5023	0.5086
<i>Average number of tugboats in use</i>	3.03	0.02	3.01	3.05

According to the comparisons of the simulation model outputs with the 2005 real data, it seems that the simulation model developed is deficient to explain the waiting time distributions at the first three months of the year (when there are extreme weather conditions in the system). However, the waiting time distributions of the remaining four months are very much comparable. Besides, the other output variables are quite satisfactory to explain the transit times and total vessels passed as well. Lastly, the average number of vessels in queues, the vessel density in the Strait, the pilot and the tugboat utilizations seem very reasonable, despite the lack of real data to compare these outputs with. Consequently, the simulation model with the external inputting structure is regarded to be sufficiently valid to represent the general behavior and trends of the real system and also to approximate the values of major performance measures of the real system, under the assumption that extreme weather conditions do not exist in the system.

5.2.2. The Comparison of the Year 2005 Statistics and the Outputs of the Simulation Model under Randomized Arrivals

The comparisons performed with external inputting of real data to the simulation model were to check the validation of the Strait entrance and vessel transition procedures followed in the simulation model. However, the scenario analyses are performed through the random generation of inputs. Thus, the simulation model with the stochastic arrival process should be compared to the real system as well.

In order to obtain similar behaviors under the same external conditions and to perform a meaningful comparison of the real system and the simulation model with the stochastic arrival process, the real visibility data of 2005 are again inputted externally to the simulation model.

The model is run for the seven months periods with 50 replications. Additionally, a one month warm-up period (December) is deployed to reach the steady-state (statistics for this month are excluded). Then, the outputs of the simulation model are compared with the year 2005 statistics.

The actual total number of vessels passed in the first seven months of 2005 and the mean of total number of vessels passed in 50 replication simulation runs are given in Table 5.9. Also, the distribution of total vessels passed in this seven months period is given in Figure 5.7. The total, southbound and northbound vessel numbers passed in the real data and in the simulation results are very close. On the other hand, the simulation outputs shows a stationary trend in the distribution of total number of vessels passed in the seven months period, whereas the real data shows fluctuations. The reason behind is that the arrival process is functioning under the assumption of random but stationary vessel arrivals to the system (i.e. random arrivals being generated through the assumed stationary probability distribution) and it is not affected by the extreme weather condition at the Black Sea. However, in the real data the vessel arrivals may be influenced (and thus show temporary increases and decreases) by adverse weather conditions at the Black Sea.

Table 5.9. The number of vessels passed in seven months in the actual 2005 data and in the simulation runs of 50 replications under randomized arrivals

<i>Direction</i>	<i>The 2005 Data</i>	<i>The Simulation Model</i>			
	<i>Total</i>	<i>Mean</i>	<i>Standard deviation</i>	<i>Lower confidence</i>	<i>Upper confidence</i>
<i>Total</i>	31411	31562	194	31488	31635
<i>NS</i>	15712	16006	119	15961	16051
<i>SN</i>	15699	15556	145	15501	15611

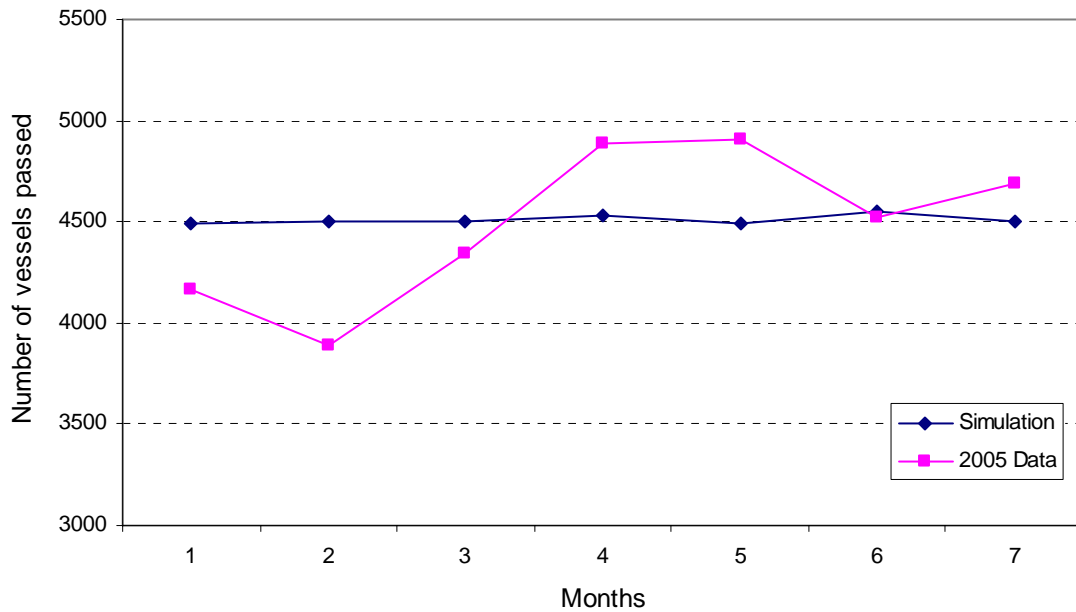


Figure 5.7. The distribution of total number of vessels passed in the first seven months of 2005 and in the simulation runs of 50 replications under randomized arrivals

The average transit time of vessels and the standard deviation of transit times in the actual 2005 data and in the 50 replication simulation runs are given in Table 5.10 and in Table 5.11. As can be seen from these tables, the means and standard deviations of transit times of total, southbound and northbound vessels do not differ too much for the indicated two cases.

Table 5.10. The average transit times in the actual 2005 data and in the simulation runs of 50 replications under randomized arrivals

Direction	The 2005 Data	The Simulation Model			
	Mean (minutes)	Mean (minutes)	Standard deviation	Lower confidence	Upper confidence
Total	103.26	102.87	0.27	102.77	102.98
NS	93.26	93.33	0.42	93.18	93.49
SN	113.31	112.70	0.83	112.38	113.01

Table 5.11. The standard deviations of transit times in the actual 2005 data and in the simulation runs of 50 replications under randomized arrivals

<i>Direction</i>	<i>The 2005 Data</i>	<i>The Simulation Model</i>			
	<i>Mean (minutes)</i>	<i>Mean</i>	<i>Standard deviation</i>	<i>Lower confidence</i>	<i>Upper confidence</i>
<i>Total</i>	21.59	19.81	0.42	19.65	19.97
<i>NS</i>	13.65	12.84	0.22	12.76	12.93
<i>SN</i>	23.36	20.88	0.39	20.74	21.03

The average waiting times of total, southbound and northbound vessels in the seven months are depicted in Figure 5.8, Figure 5.9 and Figure 5.10 respectively. As can be seen from these figures, waiting times generated by the simulation model with randomized arrivals are more representative of the real case than the results of the simulation model with external inputting structure.

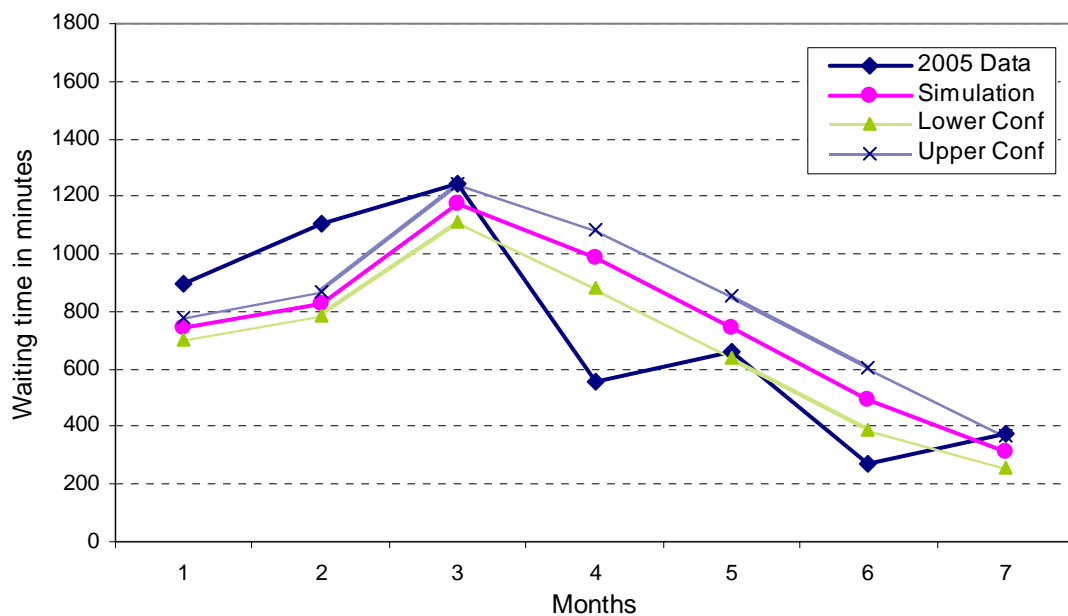


Figure 5.8. The average waiting times of total vessels in the actual 2005 data and in the simulation runs of 50 replications under randomized arrivals (January - July)

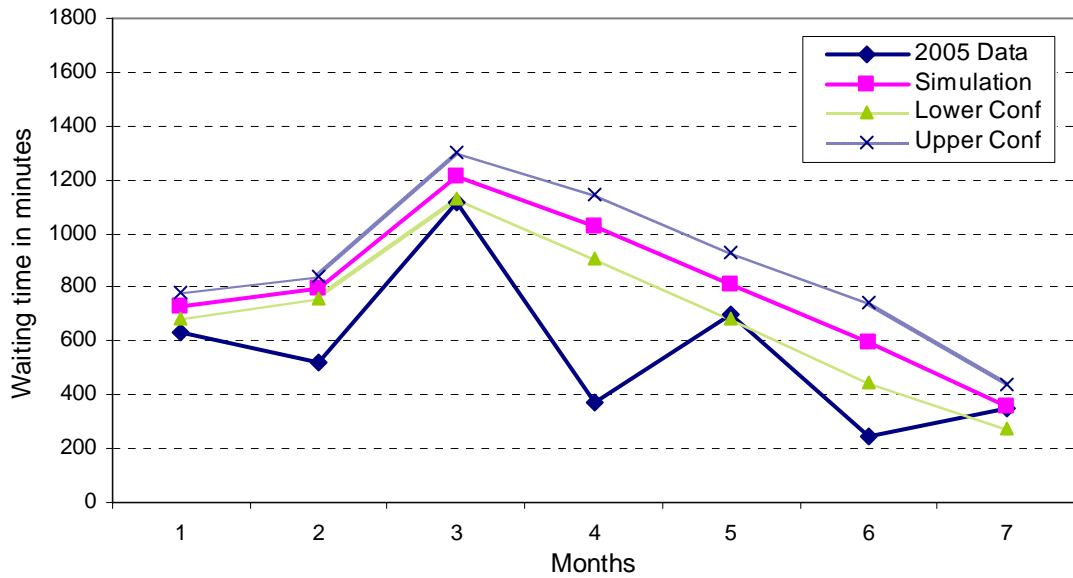


Figure 5.9. The average waiting times of southbound vessels in the actual 2005 data and in the simulation runs of 50 replications under randomized arrivals (January - July)

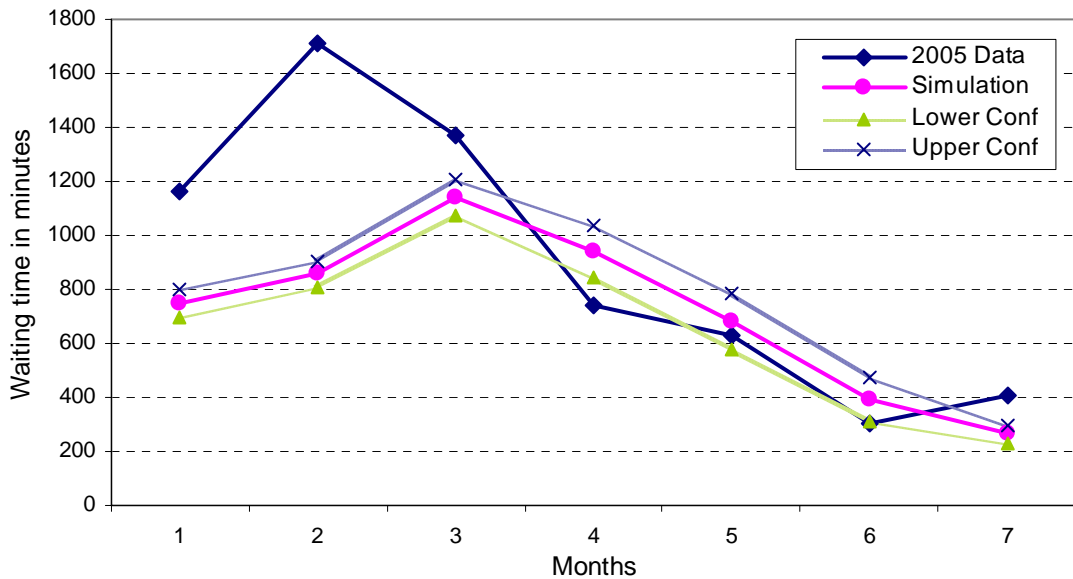


Figure 5.10. The average waiting times of northbound vessels in the actual 2005 data and in the simulation runs of 50 replications under randomized arrivals (January - July)

The average waiting time in the seven months of the actual 2005 data and in the simulation runs of 50 replications are given in Table 5.12. According to these figures, for the two cases indicated, the average waiting times of total vessels is very close, whereas southbound and northbound figures slightly differ.

Table 5.12. The average waiting times in the first seven months of the 2005 data and in the simulation runs of 50 replications under randomized arrivals

<i>Direction</i>	<i>The 2005 Data</i>	<i>The Simulation Model</i>			
	<i>Mean (minutes)</i>	<i>Mean (minutes)</i>	<i>Standard deviation</i>	<i>Lower confidence</i>	<i>Upper confidence</i>
<i>Total</i>	711.71	738.59	132.47	688.42	788.76
<i>NS</i>	560.55	774.87	160.22	714.20	835.55
<i>SN</i>	863.67	701.15	117.40	656.69	745.61

The cumulative average of number of vessels in queues in these seven months is depicted in Figure 5.11. (This average is again weighted to take into consideration the queue length as a function of time.) As can be seen from this figure, the average queue length is between 60 and 70 throughout the seven months. This value of queue length is slightly higher than the results of the simulation model with external inputting structure, but seems reasonable in accordance with the increased waiting times.

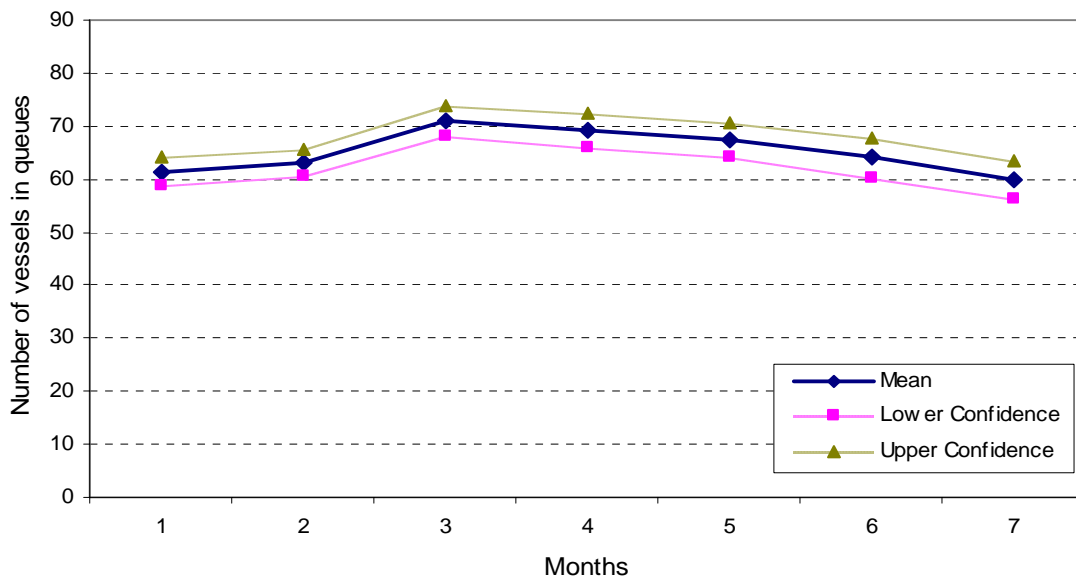


Figure 5.11. The cumulative average number of vessels in the queues in the simulation runs of 50 replications under randomized arrivals (January - July)

The vessel density and the average number of vessels in the Strait (the time persistent statistics which are weighted with respect to time) are displayed in Table 5.13. These figures indicate that on the average, there are about 11 vessels in the Strait at any time, which is consistent with the results of the simulation model with external inputting structure.

Table 5.13. The vessel density and the average number of vessels in the Strait in the simulation runs of 50 replications under randomized arrivals

	<i>Mean</i>	<i>Standard deviation</i>	<i>Lower confidence</i>	<i>Upper confidence</i>
<i>Vessel density per nautical mile in the Strait</i>	0.638	0.004	0.636	0.640
<i>Average number of vessels in the Strait</i>	10.721	0.073	10.647	10.794

The pilot and tugboat utilizations (weighted as a function of time in the Strait) are given in Table 5.14. The average number of pilots in use at any time is expected to be 4.5 of the 15 pilots and the average number of tugboats in use at any time is expected to be 3 of the 6 tugboats. These values are consistent with the results of the simulation model with external inputting.

Table 5.14. The pilot and the tugboat utilizations in the simulation runs of 50 replications under randomized arrivals

	<i>Mean</i>	<i>Standard deviation</i>	<i>Lower confidence</i>	<i>Upper confidence</i>
<i>Pilot Utilization</i>	0.2983	0.0029	0.2972	0.2994
<i>Average number of pilots in use</i>	4.47	0.04	4.46	4.49
<i>Tugboat Utilization</i>	0.5032	0.0060	0.5009	0.5055
<i>Average number of tugboats in use</i>	3.02	0.04	3.01	3.03

According to the comparisons of the outputs of the simulation model with stochastic arrivals with the actual 2005 data, the general behavior of the system and trends are well represented. Since the arrival process to the system is assumed to be stationary, the real vessel transit trend in the first months can not be captured well. However, the waiting time distributions, and the other output parameters are very satisfactory to explain the real situation. Besides, the average number of vessels in queues, the vessel density in the Strait, the pilot and the tugboat utilizations seem very reasonable and consistent with the simulation model having external inputting structure. Consequently, this simulation model is thought to be sufficiently valid to perform scenario analysis on the concerned performance measures, under the assumption that vessel arrivals are stationary in time and extreme weather conditions at the Black Sea do not affect vessel arrivals and the vessel priorities in the system.

6. SCENARIO ANALYSIS AND RESULTS

In this section simulation experiments which are designed to reach a better understanding and control of the overall effects of multiple factors are discussed. In addition, since the performance of the existing system under some projected set of operating conditions is tried to be estimated, these experiments imply scenario analysis.

6.1. Design of Simulation Experiments

When a model has only one factor the experimental design is conceptually simple. That is confidence intervals can be formed for the concerned performance measures at each of the factor levels. When there are multiple factors, the questions are how each factor affects the performance measures and whether the factors interact with each other. That is, the effect of one factor depends on the levels of the others.

The seven factors of concern in the scenario analysis of the Strait of Istanbul Traffic Simulation model are:

- Arrival rates of transit vessels,
- Vessel profiles,
- Pilot and tugboat availabilities,
- Current conditions,
- Kandilli region encounter prevention rule,
- Pursuit distance between vessels,
- Seasonal conditions which also represents visibility conditions.

Through simulation experiments, the influence of these factors on the performance measures and interactions with each other are investigated. Factorial designs are most efficient way for this type of experiments involving multiple factors at various levels. By a factorial design, in each complete trial or replication of the experiment, all possible combinations of the levels of the factors are investigated. An important case of factorial

design with k factors each at only two levels, requires 2^k observations and is called 2^k factorial design (Montgomery, 2001).

The disadvantage of factorial designs is that they require a large number of distinct runs when the number of factors or the numbers of levels of the factors are large. In the scenario analysis of a 2^7 design of seven factors, each at two levels, requires 128 scenarios and 10 replications to obtain more reliable estimates of the effects requires 1280 simulation runs. In many cases large number of simulation runs are not practical or feasible (due to time constraints).

In this case fractional factorials, which are fractions of the complete factorial experiment, are often employed. When certain high-order interactions are negligible, information on the main effects and low-order interactions may be obtained through fractional factorial designs. A one-half fraction of a 2^7 design contains $2^{7-1} = 64$ scenarios and 10 replications requires 640 observations, which is a reasonable amount and affordable.

6.1.1. The Factors and Levels

The seven factors and their levels deployed in 64 distinct scenarios are displayed in Table 6.1.

Table 6.1. Factors and levels in the scenario analysis

<i>Factor</i>	<i>Name</i>	<i>Low</i>	<i>High</i>
<i>A</i>	<i>Arrival Rate</i>	Normal	High
<i>B</i>	<i>Vessel Profile</i>	Normal	HazMat High
<i>C</i>	<i>Pilot/Tugboat</i>	20/9	15/6
<i>D</i>	<i>Current Profile</i>	Normal	High
<i>E</i>	<i>Kandilli Rule</i>	Normal	Conservative
<i>F</i>	<i>Pursuit Distance</i>	4 cables	8 cables
<i>G</i>	<i>Season</i>	Summer	Winter

Specifying the levels of the factors under consideration needs further discussion since there is no general prescription. Generally, the levels should not be very far apart from each other and levels of different factors can be determined in a sense to balance the output values. On the other hand, if the response is highly variable the short distance

between levels may cause misleading conclusion that estimated factor effect is insignificant. Thus, intuitive feel for the model and the realistic conditions are considered to specify reasonable values for the quantitative factors and meaningful options for the qualitative factors (Law and Kelton, 2000; Montgomery, 2001).

The arrival rate refers to the arrival frequency of transit vessels and thus, the total number of transit vessels coming to the Strait of Istanbul. The interarrival time distribution for each cluster of transit vessels used in the model is based on the year 2005 vessel arrivals (see Table A.1 and Table A.3) and thus, defines the ‘Normal’ setting of the arrival rate (which is 150 vessels per day on the average). In the ‘High’ setting of the arrival rate, the total number of transit vessels is increased by 15 per cent, through modifying the interarrival time distributions of all clusters in a way that to reduce each generated interarrival time by 15 per cent.

Vessel profile refers to the frequency distribution of vessels according to their types. The ‘Normal’ setting of the vessel profile corresponds to the profile resulting through arrival process based on the year 2005 vessel arrivals. The ‘HazMat High’ setting reflects the situation of having 10 per cent of the general cargo carrying vessels converted into hazardous material carrying vessels (in the 2005 data). A representation of the normal and HazMat high vessel profile settings based on the 2005 statistics is given in Table 6.2.

Table 6.2. Frequency distribution of vessel types in Normal and HazMat profiles based on vessels transited in 2005

<i>Vessel Type</i>	<i>Normal Profile</i>	<i>HazMat High Profile</i>
<i>Passenger</i>	0.027	0.027
<i>LNG-LPG</i>	0.006	0.006
<i>Hazardous Material</i>	0.015	0.094
<i>Tanker</i>	0.167	0.167
<i>General Cargo</i>	0.784	0.706
<i>Total</i>	1.000	1.000

Pilot/tugboat levels used in the scenario analysis are the current real situation of 15 pilot captains and six tugboats in the high settings and prospective levels of 20 pilot captains and nine tugboats in the low settings.

The current profile in the Strait depends on a randomly generated daily magnitude in a specified station. This magnitude is then reflected to the whole Strait via appropriate predetermined percentage factors. In the ‘Normal’ setting of the current profile the expected mean of the randomly generated daily peak value occurs at about 2.7 knots. The ‘High’ setting of the current profile corresponds to a 30 per cent increase in current speeds such that the expected mean of the randomly generated daily peak value occurs at about 3.5 knots.

Kandilli encounter prevention rule reflects an important Strait Regulation. 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 speeds of the vessels in the Strait are hard to predict, this rule needs to be applied within a confidence factor. In the ‘Normal’ settings of the confidence factor, Strait entry times of vessels are regulated so that potential undesirable encounters (based on expected transit speeds) will not take place within two stations in each direction of the Kandilli region. While in the ‘Conservative’ setting of the confidence factor, potential undesirable encounters are avoided within four stations in each direction of the region.

According to the Strait Regulations vessels in transit in the Strait have to maintain a pursuit distance of at least eight cables. This distance is designed as a parameter in the simulation model and can vary between 2 cables to 10 cables in order to evaluate the effect of pursuit distance in the vessel transitions. In the scenario analysis four cables and eight cables are used for the low and the high settings respectively as the pursuit distance.

The seasons affect vessel transits in the Strait through seasonality of fog occurrences and through changing lengths of daytime and nighttime. The seasons used in the simulation runs are winter and summer. In the scenario analysis the winter season includes November and December as the warm-up period and months from January to April as the normal simulation period of four months length. The summer season includes March and April as the warm-up period and months between May and August is the normal simulation period.

6.1.2. Output Performance Measures

In experimental design terminology the output performance measures are called responses. The effects of factors is investigated on the following responses through scenario analysis;

- The number of vessels that have completed their transit,
- The average transit time of vessels (that have completed their transit),
- The average waiting time of vessels (that have completed their transit),
- The maximum waiting time of vessels (that have completed their transit),
- The number of vessels in the queues (still waiting for transit),
- The vessel density in the Strait (number of transit vessels per mile),
- The pilot utilization (ratio of total busy time to total available time),
- The tugboat utilization (ratio of total busy time to total available time).

6.1.3. 2^{7-1}_{VII} Design

In the scenario analysis the 2^{7-1} fractional factorial design with 10 replications is adopted. This design requires 64 scenario runs with 10 replications each. In the fractional factorial designs high-order interactions are neglected and information on main effects and low-order interactions can be obtained.

Specifically, the 2^{7-1} design used is of resolution VII of which the defining relation is $I = ABCDEFG$. That is, a design is of resolution R if no p -factor effect is aliased with another effect containing less than $R - p$ factors. In the 2^{7-1}_{VII} design, each main effect is aliased with a single six-factor interaction; each two-factor interaction is aliased with a single five-factor interaction and each three factor interaction is aliased with a single four-factor interaction (Montgomery, 2001).

6.2. Results of the Scenario Analysis

The 10 replications of the 64 scenarios are run for a six month (in which two months warm-up is included). The outputs for each scenario are collected and analyzed through Design Expert 7.0 software in order to evaluate the effects of the determined factors on the selected response variables (Table B.1 and Table B.2).

The significant factors and factor interactions are determined through an iterative process which includes transformation selection (if needed), choosing significant effects and analyzing the model through ANOVA tables, evaluating model fit and assumptions and interpreting results in the Design Expert software.

The problem of non constant variance in the response variables is a departure from the standard analysis of variance assumptions. In this case, the transformation of the response variable is an appropriate method for stabilizing the variance of the response. Transformations are also used for getting the distribution of the response variable closer to the normal distribution and improving the fit of the model to the data. On the other hand, transformations often have little effect unless the response value ratio of maximum to minimum is larger than two or three. Box-Cox procedure of the Design Expert for selecting a power family transformation is used in the analysis of several responses (Montgomery, 2001).

In analyzing the model through ANOVA tables, factors are added to the model according to normal plots of standardized effects and Pareto charts unless there are non significant terms. Thus, all of the significant terms are tried to be captured. The ANOVA tables on each response are given in Appendix C. Besides, the model graphs on each significant main factor and two-way factor interactions are displayed for each response in Appendix C and the detailed results are discussed in the following sections.

The overall results for the per cent contributions of the significant main factors and significant factor interactions to explain the variance of the responses among scenario runs are given in Table 6.3 and Table 6.4 respectively. In these tables the positive effects are denoted with (+) sign and negative effects are denoted with (-) sign.

Table 6.3. Percent contributions of significant main factors on the variance of responses

Responses / Factors	A	B	C	D	E	F	G
	<i>Arrival rate</i>	<i>Vessel profile</i>	<i>Pilot / TugBoat</i>	<i>Current profile</i>	<i>Kandilli rule</i>	<i>Pursuit distance</i>	<i>Season</i>
<i>Number of vessels passed</i>	(+) 98.72		(-) 0.08				(-) 0.02
<i>Avg transit times of vessels</i>	(+) 8.02	(+) 0.10	(-) 1.67	(+) 9.76		(+) 77.26	
<i>Avg waiting times of vessels</i>	(+) 41.00	(+) 7.79	(+) 30.02	(+) 0.62	(+) 0.14	(+) 2.32	(+) 9.03
<i>Max waiting times of vessels</i>	(+) 37.23	(+) 4.07	(+) 28.60	(+) 2.50		(+) 0.49	(+) 8.34
<i>Number of vessels in queues</i>	(+) 48.19	(+) 7.17	(+) 30.79	(+) 0.29	(+) 0.14	(+) 2.68	(+) 3.84
<i>Vessel density in the Strait</i>	(+) 91.68		(-) 0.39	(+) 0.70		(+) 5.73	
<i>Pilot utilizations</i>	(+) 26.6		(+) 70.40	(+) 0.24		(+) 1.91	
<i>Tugboat utilizations</i>	(+) 15.1		(+) 83.15	(+) 0.17		(+) 0.91	

Table 6.4. Percent contributions of significant factor interactions on the variance of responses

Responses / Factors	AB	AC	AD	AF	AG	CF	BC	CG	DG	ABC	ACG
	<i>Arrival rate - Vessel profile</i>	<i>Arrival rate - Pilot / Tugboat</i>	<i>Arrival rate - Current profile</i>	<i>Arrival rate - Pursuit distance</i>	<i>Arrival rate - Season</i>	<i>Pilot / Tugboat - Pursuit distance</i>	<i>Vessel profile - Pilot / Tugboat</i>	<i>Pilot / Tugboat - Season</i>	<i>Current profile - Season</i>	<i>Arrival rate - Vessel profile - Pilot / Tugboat</i>	<i>Arrival rate - Pilot / Tugboat - Season</i>
<i>Number of vessels passed</i>		(-) 0.06									
<i>Avg transit times of vessels</i>		(-) 0.37		(+) 0.77		(-) 0.07					
<i>Avg waiting times of vessels</i>	(-) 0.09	(+) 1.72			(-) 0.04		(-) 0.09	(-) 1.69		(-) 0.52	(-) 2.66
<i>Max waiting times of vessels</i>		(+) 7.29	(-) 0.49		(-) 0.08			(-) 0.27	(-) 0.48		(-) 3.81
<i>Number of vessels in queues</i>		(+) 2.63			(-) 0.04			(-) 0.95			(-) 1.14
<i>Vessel density in the Strait</i>		(-) 0.17		(+) 0.15							
<i>Pilot utilizations</i>		(+) 0.19		(+) 0.05							
<i>Tugboat utilizations</i>		(+) 0.19		(+) 0.02							

Table 6.3 and Table 6.4 point out the importance of factors on the increase or decrease of an output performance measure. For example, 98.72 per cent of the variation in the number of vessels passed is caused by the change in the arrival rate and 15 per cent increase of the arrival rate (which is the case in the ‘High’) setting, positively effects number of vessels passed. Besides, pilot/tugboat availability, seasons and interaction effect between arrival rate and pilot/tugboat availability have little but significant influence on the number of vessels passed.

6.2.1. The Number of Vessels That Have Completed Their Transit

The significant factors affecting the number of vessels that have completed their transit (passed) are selected through the normal probability plot of the standardized effects depicted in Figure 6.1.

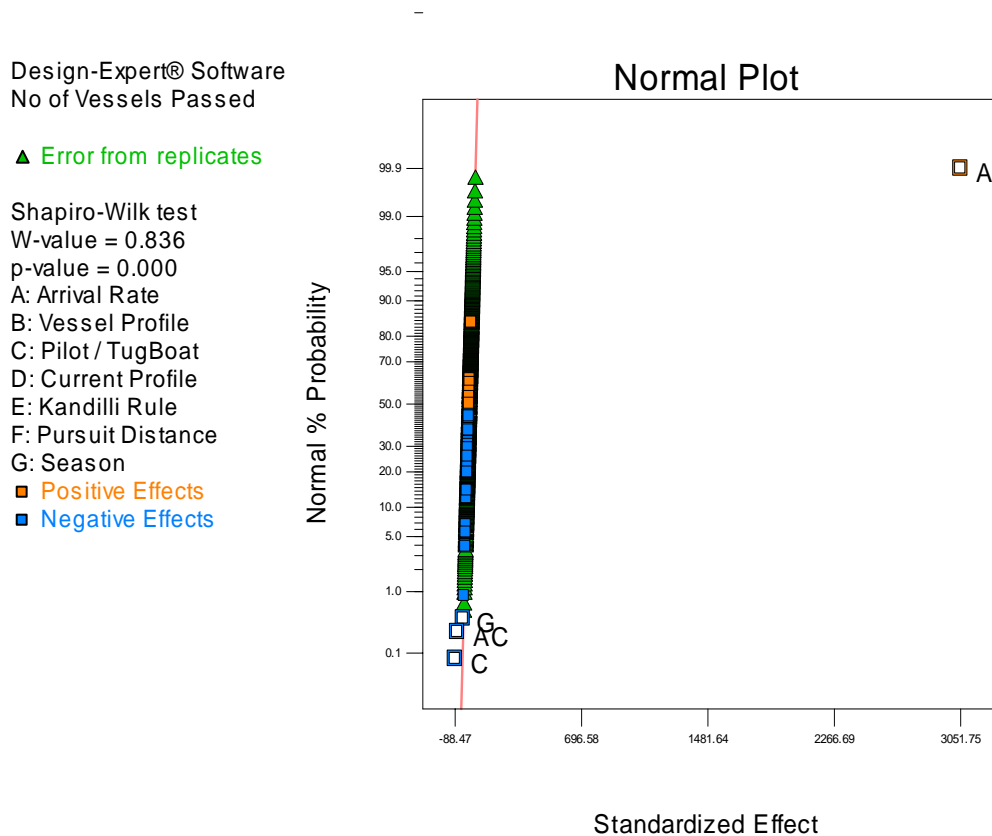


Figure 6.1. The normal probability plot of the effects for number of vessels that have completed their transit

The selected factors are evaluated in the ANOVA table displayed in Table C.1. The model p-value (which is less than 0.01) indicates that the model is significant and the significant model terms are A, C, G and AC. The ‘Pred R-squared’ value of 0.9886 is in reasonable agreement with the ‘Adj R-squared’ value of 0.9887. (According to Montgomery (2001), a difference greater than 0.2 between ‘Pred R-squared’ and ‘Adj R-squared’ values would indicate a possible problem with the model or the data.)

In order to check the assumptions of the model, the normal probability plot of residuals and residuals versus predicted response values graphs are checked. These graphs do not indicate great distortions from the normality assumption of residuals and constant variance assumptions. The Box-Cox procedure for power transformation is not applied for this response since the model fit is sufficient and the response value ratio of maximum to minimum is about 1.21 (Montgomery, 2001).

The significant factors’ standardized effects and the per cent contributions to explain the variance of the responses are given in Table 6.5. Besides, the model graphs of the factors and factor interactions are displayed in Appendix C.

Table 6.5. The standardized effects and per cent contributions for number of vessels that have completed their transit

	<i>Factors</i>	<i>Standardized effect</i>	<i>Per cent contribution</i>
A	<i>Arrival rate</i>	3051.75	98.72
C	<i>Pilot / Tugboat</i>	-88.47	0.08
G	<i>Season</i>	-38.56	0.02
AC	<i>Arrival rate - Pilot / Tugboat</i>	-73.96	0.06

In Table 6.5 the most important factor on the number of vessels passed is obviously the arrival rate, (or equivalently, the total number of vessels arrived to the system in a given time). In addition, pilot / tugboat availability and season have significant influence on the number of vessels passed although the percent contribution and model graphs in Figure C.2 and Figure C.3 indicate a weak relation. Furthermore, it can be inferred from the arrival rate and pilot / tugboat interaction that available numbers of pilot / tugboats are more effective when the arrival rate is high.

6.2.2. The Average Transit Times of Vessels

The normal probability plot of the standardized effects of the significant factors affecting the average transit times of vessels are depicted in Figure 6.2.

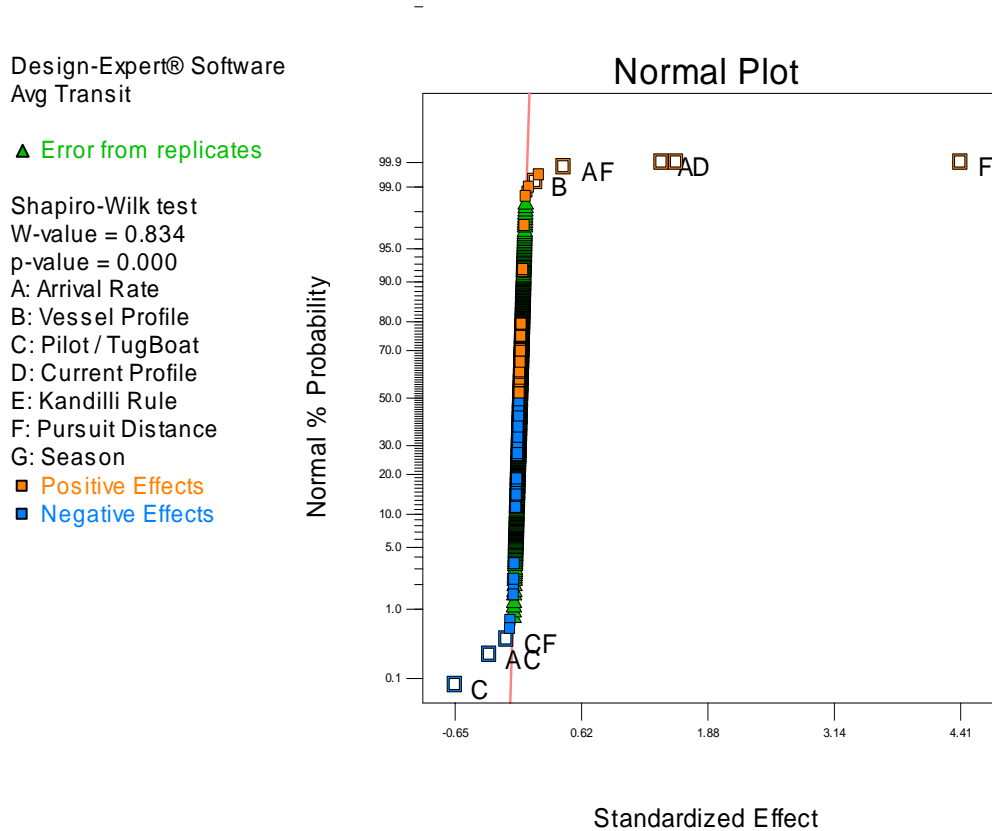


Figure 6.2. Normal probability plot of the effects for average transit times

The ANOVA table displayed in Table C.2 indicates that the model is significant and the model adequacy checks shows that the assumptions are satisfied. The model graphs are also displayed in Appendix C.

The significant model terms and their percent contributions are given in Table 6.6.

Table 6.6. The standardized effects and per cent contributions for average transit times

	<i>Factors</i>	<i>Standardized effect</i>	<i>Per cent contribution</i>
<i>A</i>	<i>Arrival rate</i>	1.42	8.02
<i>B</i>	<i>Vessel profile</i>	0.16	0.1
<i>C</i>	<i>Pilot / Tugboat</i>	-0.65	1.67
<i>D</i>	<i>Current profile</i>	1.57	9.76
<i>F</i>	<i>Pursuit distance</i>	4.41	77.26
<i>AC</i>	<i>Arrival rate - Pilot / Tugboat</i>	-0.3	0.37
<i>AF</i>	<i>Arrival rate - Pursuit distance</i>	0.44	0.77
<i>CF</i>	<i>Pilot / Tugboat - Pursuit distance</i>	-0.13	0.07

The most important factor affecting the transit time of vessels is pursuit distance between vessels. The implicit reason for that is short pursuit distance facilitates overtaking between vessels. That is, high speed vessels can overtake low speed vessels easily when the allowed pursuit distance is low and thereby cause a decrease in the average transit times of vessels.

Another important factor on transit times is the current profile. Current speeds throughout the Strait directly affect vessels' speeds. In general, the primary southbound current flow increases the speeds of southbound vessels while decreasing the speed of northbound vessels. However, due to the effective speeds of vessels in the Strait, higher levels of current profile generally causes an increase in the average transit times of vessels.

The arrival rate has indirect influence on the transit times through affecting the vessel density in the Strait. Higher arrival rates leads to higher vessel densities in the Strait, in which case overtaking conditions get harder to satisfy and faster vessels are obliged to proceed behind slower vessels. Thus, high arrival rate increase the average transit times in the Strait.

The other significant factors, pilot / tugboat availability, vessel profile, arrival rate and pilot / tugboat interaction, arrival rate and pursuit distance interaction and lastly pilot / tugboat and pursuit distance interaction, are also indirectly influential on the transit time through affecting vessel density in the Strait. When the arrival rate is high, the available pilot/tugboat level of 20/9 increases the number of vessels entering to the Strait, and thus decreasing transit times. Arrival rate and pursuit distance interaction and pilot/tugboat and pursuit distance interaction work in a similar way and affect the transit times.

6.2.3. The Average Waiting Times of Vessels

In the analysis of the average waiting times of vessels, natural log transformation on the response values is used through the Box-Cox procedure of Design Expert to stabilize response variance and to improve model fit. The normal probability plot of the standardized effects of the significant factors are displayed in Figure 6.3.

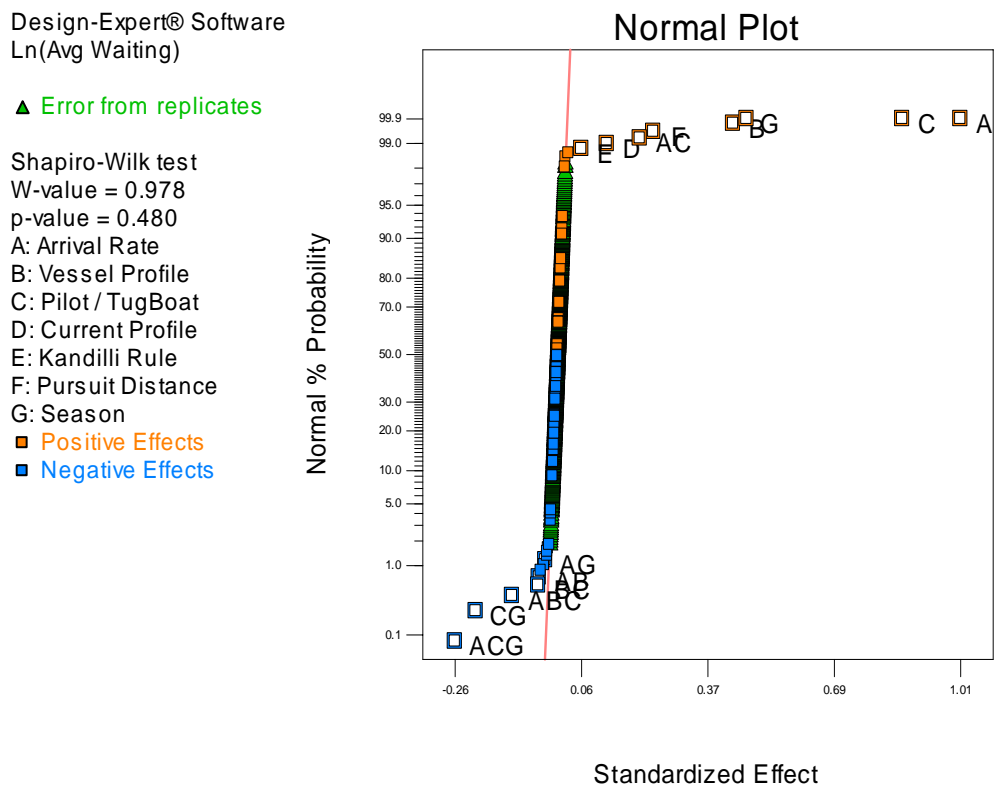


Figure 6.3. The normal probability plot of the effects for average waiting times

The ANOVA table in Table C.3 indicates that the model is significant. The model adequacy checks are also performed. In Appendix C the model graphs are displayed and the significant model terms and their percent contributions are given in Table 6.7.

Table 6.7. The standardized effects and per cent contributions for average waiting times

	<i>Factors</i>	<i>Standardized effect</i>	<i>Per cent contribution</i>
A	<i>Arrival rate</i>	1.01	41
B	<i>Vessel profile</i>	0.44	7.79
C	<i>Pilot / Tugboat</i>	0.86	30.02
D	<i>Current profile</i>	0.12	0.62
E	<i>Kandilli rule</i>	0.06	0.14
F	<i>Pursuit distance</i>	0.24	2.32
G	<i>Season</i>	0.47	9.03
AB	<i>Arrival rate - Vessel profile</i>	-0.046	0.09
AC	<i>Arrival rate - Pilot / Tugboat</i>	0.21	1.72
AG	<i>Arrival rate - Season</i>	-0.03	0.04
BC	<i>Vessel profile - Pilot / Tugboat</i>	-0.048	0.09
CG	<i>Pilot / Tugboat - Season</i>	-0.2	1.69
ABC	<i>Arrival rate - Vessel profile - Pilot / Tugboat</i>	-0.11	0.52
ACG	<i>Arrival rate - Pilot / Tugboat - Season</i>	-0.26	2.66

According to Table 6.7 the most important factors affecting the average waiting times of vessels are surely the arrival rate and the pilot / tugboat availability. The effects of these factors are explicit in that the service rate cannot meet the demand when demand is high or when the resources are insufficient.

The season, the vessel profile and the pursuit distance have also important effects. The effect of the season is due to visibility issues and having short daytime length in the winter season. The influence of the vessel profile arises due to the increase in the hazardous material carrying vessels which are exposed to stricter Strait Regulations. The pursuit distance effects the waiting time since low levels of pursuit distance increase the service rate thorough increasing the frequency of vessel permissions into the Strait.

The current profile and the Kandilli encounter prevention rule also have significant but relatively low importance regarding waiting time. The effect of current profile arises due to vessel restrictions into the Strait when high current conditions observed. Clearly, a conservative application of the Kandilli rule can cause an increase in the waiting time of vessels.

Apart from these main factors, interactions of several factors also have significant effects on the average waiting time. Especially,

- (i) arrival rate, pilot / tugboat and season interaction,

- (ii) arrival rate and pilot / tugboat interaction,
- (iii) pilot / tugboat and season interaction

have important effects. It is obvious from these interactions that effects of important factors such as the pilot / tugboat availability and the season increase when especially the arrival rate increases. These interactions can be better understood from the interaction graphs in Appendix C.

6.2.4. The Maximum Waiting Time of Vessels

In the analysis of the maximum waiting times of vessels, natural log transformation is used through the Box-Cox procedure of Design Expert. The normal probability plot of standardized effects of the significant factors are displayed in Figure 6.4.

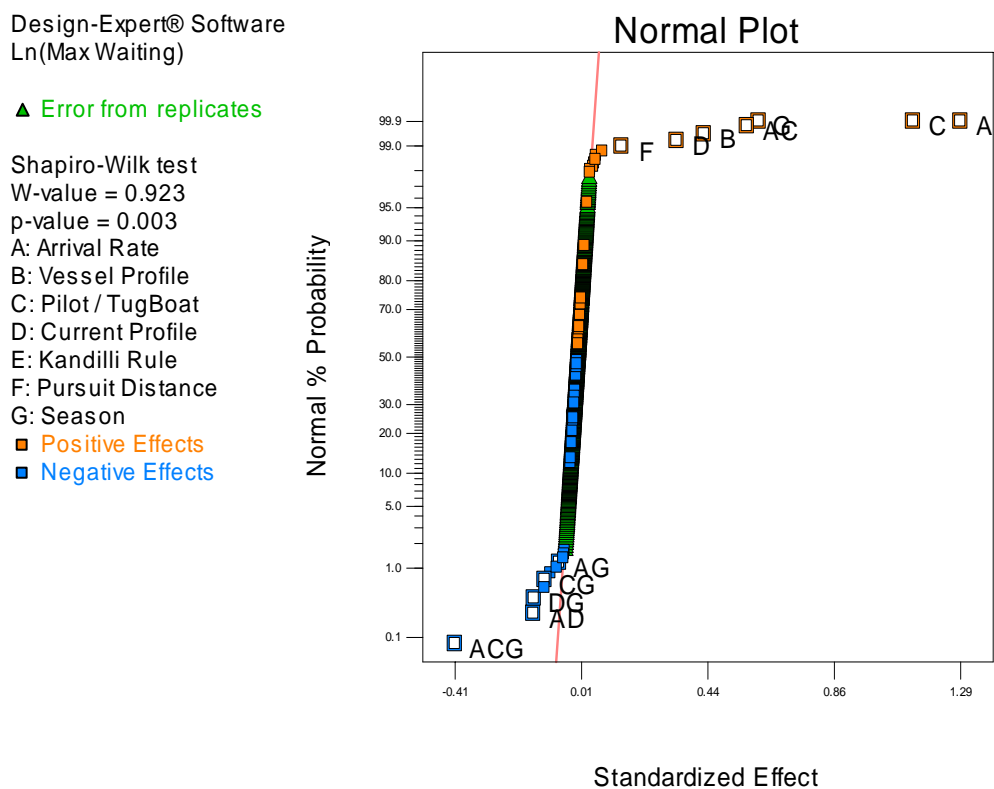


Figure 6.4. The normal probability plot of the effects for maximum waiting times

The model is significant according to the ANOVA table in Table C.4 and the assumptions are satisfied through model adequacy checks. The model graphs are also displayed in Appendix C and the significant model terms and their percent contributions are given in Table 6.8. The factors affecting the maximum waiting time are similar to factors affecting the average waiting time. However, the importance of factors are slightly changed.

Table 6.8. The standardized effects and per cent contributions for maximum waiting times

	<i>Factors</i>	<i>Standardized effect</i>	<i>Per cent contribution</i>
A	<i>Arrival rate</i>	1.29	37.23
B	<i>Vessel profile</i>	0.43	4.07
C	<i>Pilot / Tugboat</i>	1.13	28.6
D	<i>Current profile</i>	0.33	2.5
F	<i>Pursuit distance</i>	0.15	0.49
G	<i>Season</i>	0.61	8.34
AC	<i>Arrival rate - Pilot / Tugboat</i>	0.57	7.29
AD	<i>Arrival rate - Current</i>	-0.15	0.49
AG	<i>Arrival rate - Season</i>	-0.061	0.08
CG	<i>Pilot / Tugboat - Season</i>	-0.11	0.27
DG	<i>Current profile - Season</i>	-0.15	0.48
ACG	<i>Arrival rate - Pilot / Tugboat - Season</i>	-0.41	3.81

The most important factors affecting the maximum waiting time are the arrival rate and the pilot / tugboat availability (as they are in the average waiting time case). Besides, the season and the vessel profile also have important effects. However, the effect of pursuit distance is decreased and the effect of current profile is increased compared to their effects on the average waiting time. It is clear that the pursuit distance has more balanced influence on all vessels, but the current profile may affect some vessels more severely, since its magnitude changes daily in the simulation runs.

The effects of interacting factors also changed compared to their effects on the average waiting time. Arrival rate and pilot / tugboat interaction and additional season interaction have important effects on the maximum waiting time response. The importance of the pilot / tugboat availability increases when the arrival rate increases. Besides, season interacts with this relation as well.

6.2.5. The Number of Vessels in Queues

In the analysis of the number of vessels in queues, natural log transformation is used through the Box-Cox procedure of Design Expert. The normal probability plot of the standardized effects of the significant factors are displayed in Figure 6.5.

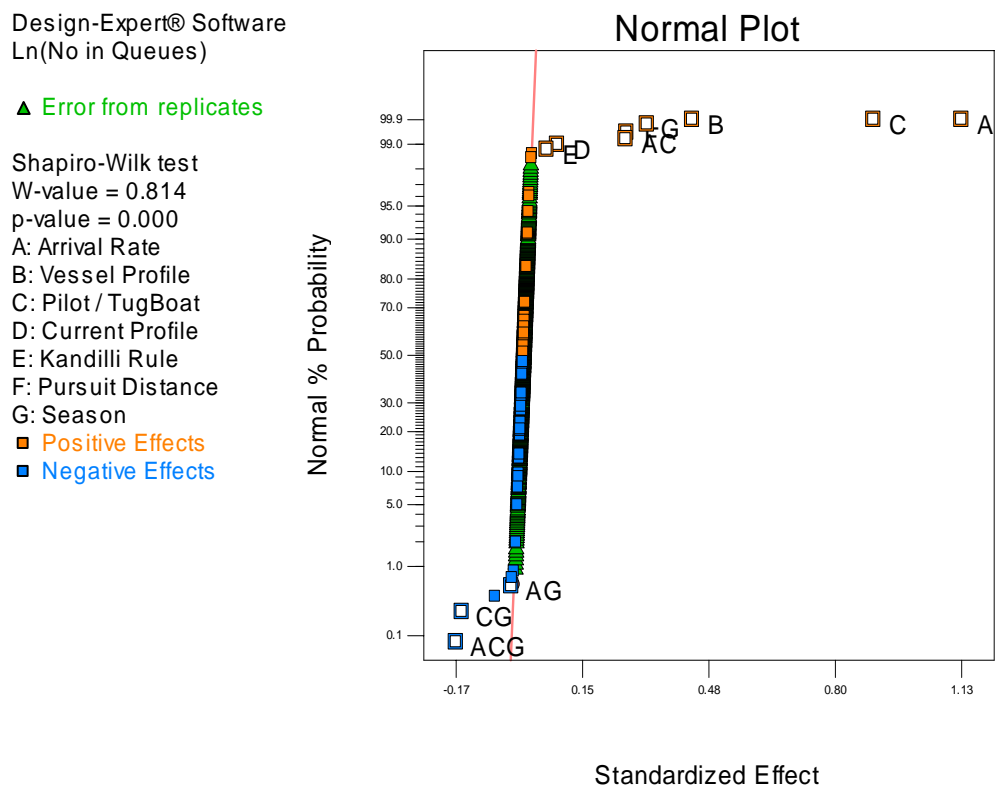


Figure 6.5. The normal probability plot of the effects for number of vessels in queues

The ANOVA table in Table C.5 indicates that the model is significant and its assumptions are satisfied through model adequacy checks. The model graphs are displayed in Appendix C and the significant model terms and their percent contributions are given in Table 6.9.

Table 6.9. The standardized effects and per cent contributions for number of vessels in queues

	<i>Factors</i>	<i>Standardized effect</i>	<i>Per cent contribution</i>
<i>A</i>	<i>Arrival rate</i>	1.13	48.19
<i>B</i>	<i>Vessel profile</i>	0.44	7.17
<i>C</i>	<i>Pilot / Tugboat</i>	0.9	30.79
<i>D</i>	<i>Current profile</i>	0.087	0.29
<i>E</i>	<i>Kandilli rule</i>	0.061	0.14
<i>F</i>	<i>Pursuit distance</i>	0.27	2.68
<i>G</i>	<i>Season</i>	0.32	3.84
<i>AC</i>	<i>Arrival rate - Pilot / Tugboat</i>	0.26	2.63
<i>AG</i>	<i>Arrival rate - Season</i>	-0.031	0.04
<i>CG</i>	<i>Pilot / Tugboat - Season</i>	-0.16	0.95
<i>ACG</i>	<i>Arrival rate - Pilot / Tugboat - Season</i>	-0.17	1.14

The most effective factors on the number of vessels waiting in the queues are the arrival rate and the pilot / tugboat availability. Since these factors increase the waiting time of vessels, they also increase the number of vessels waiting in the queues.

The other important factors are the vessel profile, the season and the pursuit distance. The current profile and the Kandilli rule have also significant but less important effects. These factors affect the number of vessels in the queues in the same way that they affect waiting times of vessels.

The factor interactions of arrival rate, pilot / tugboat availability and season also have a significant effect on the number of vessels in queues.

6.2.6. The Vessel Density in the Strait

The significant factors affecting the vessel density in the Strait are selected through the normal probability plot of the standardized effects displayed in Figure 6.6.

The ANOVA table in Table C.6 indicates that the model is significant and its assumptions are satisfied through model adequacy checks. The model graphs are displayed in Appendix C and the significant model terms and their percent contributions are given in Table 6.10

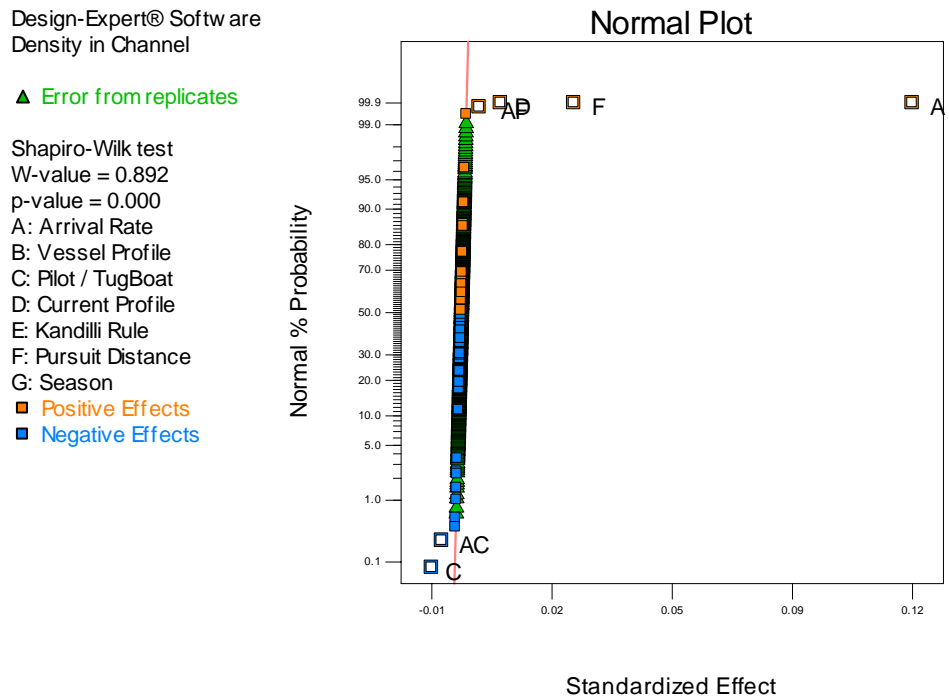


Figure 6.6. The normal probability plot of the effects for vessel density in the Strait

Table 6.10. The standardized effects and per cent contributions for vessel density in the Strait

	<i>Factors</i>	<i>Standardized effect</i>	<i>Per cent contribution</i>
A	<i>Arrival rate</i>	0.12	91.68
C	<i>Pilot / Tugboat</i>	-0.008	0.39
D	<i>Current profile</i>	0.01	0.7
F	<i>Pursuit distance</i>	0.029	5.73
AC	<i>Arrival rate - Pilot / Tugboat</i>	-0.005	0.17
AF	<i>Arrival rate - Pursuit distance</i>	0.005	0.15

The arrival rate is the most considerable factor affecting the vessel density in the Strait. Since the vessel transits in the Strait increase under high arrival rates, the vessel density in the Strait per unit time will also increase.

The pursuit distance has an indirect effect on the Strait vessel density. That is, short pursuit distances decrease the transit time of vessels in the Strait through better facilitating overtaking conditions. Thus, short transit times decrease the long run average vessel density in the Strait. In fact short pursuit distances may bring about a short term increase in

the Strait vessel density but, in the long run, it causes a decrease in the vessel density through decreasing transit time.

Current profile also has a significant effect on the vessel density, through its effect on the transit time. A high level of current profile increases transit times and high transit times in turn increase the vessel density.

The pilot / tugboat availability has very little but significant effect on the Strait vessel density. When the pilot / tugboat level is 15/6, the vessel density slightly decreases, but when the pilot / tugboat level is 20/9, the vessel density slightly increases, since it is easier to find a pilot / tugboat and thus easier to enter the Strait.

The arrival rate and the pursuit distance interaction and the arrival rate and the pilot / tugboat interaction slightly affect the vessel density. Under higher arrival rates, changes in the level of pursuit distance or in the pilot / tugboat level has more evident effects on the vessel density.

6.2.7. The Pilot Utilization

The normal probability plot of the standardized effects of the related significant factors are displayed in Figure 6.7.

The ANOVA table displayed in Table C.7 indicates that the model is significant and the model adequacy checks show that assumptions are satisfied. The model graphs are also displayed in Appendix C.

The significant model terms and their percent contributions are given in Table 6.11.

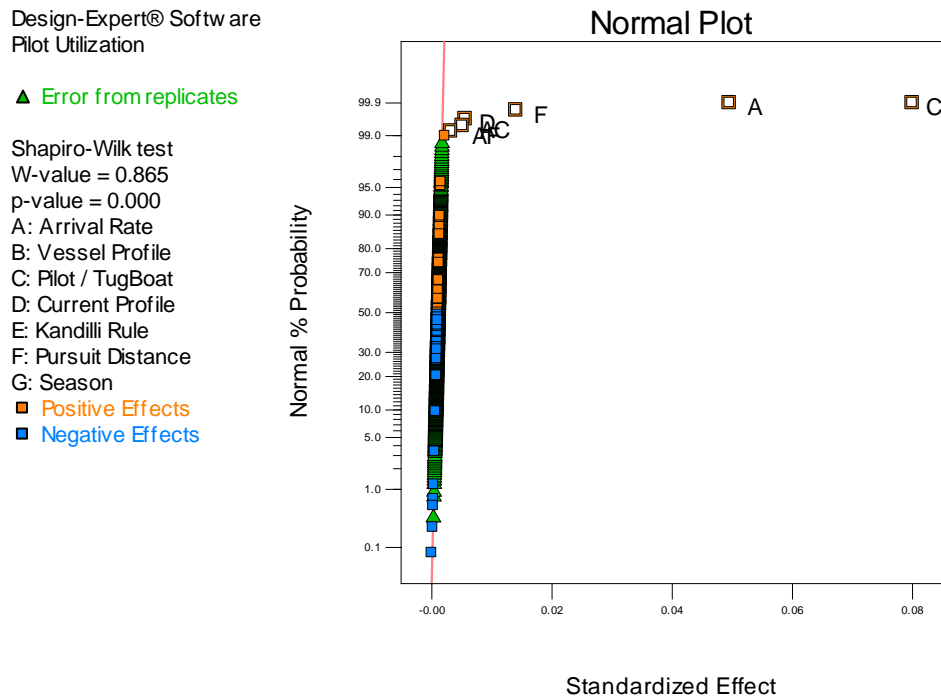


Figure 6.7. The normal probability plot of the effects for pilot utilization

Table 6.11. The standardized effects and per cent contributions for pilot utilization

	<i>Factors</i>	<i>Standardized effect</i>	<i>Per cent contribution</i>
A	Arrival rate	0.047	26.6
C	Pilot / Tugboat	0.076	70.4
D	Current profile	0.004	0.24
F	Pursuit distance	0.012	1.91
AC	Arrival rate - Pilot / Tugboat	0.004	0.19
AF	Arrival rate - Pursuit distance	0.002	0.05

The pilot / tugboat availability and the arrival rate have clearly the most important effects on the pilot utilization. When the pilot / tugboat level is 15/6 or when the arrival rate increases the pilot utilization increase as well.

The pursuit distance and the current profile also have important effects since they affect the transit times of vessels. When transit times increase pilot utilization also increases. Thus, high levels of the pursuit distance or the current profile positively effects the pilot utilization.

The arrival rate and the pilot / tugboat interaction and the arrival rate and the pursuit distance interaction also have slight effects on the pilot utilization. Under higher arrival rates the effect of pilot / tugboat availability or the effect of pursuit distance is clearer.

6.2.8. The Tugboat Utilization

The normal probability plot of the standardized effects of the related significant factors are displayed in Figure 6.8.

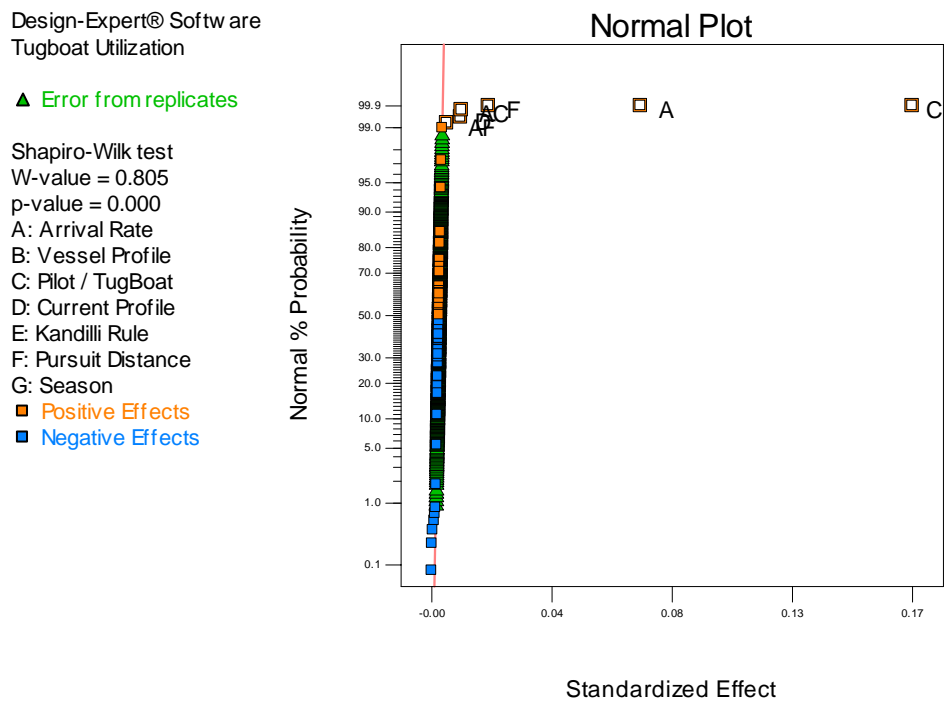


Figure 6.8. The normal probability plot of the effects for tugboat utilization

The ANOVA table displayed in Table C.8 indicates that the model is significant and its assumptions are satisfied through model adequacy checks. The model graphs are also displayed in Appendix C.

The significant model terms and their percent contributions are given in Table 6.12.

Table 6.12. The standardized effects and per cent contributions for tugboat utilization

	<i>Factors</i>	<i>Standardized effect</i>	<i>Per cent contribution</i>
<i>A</i>	<i>Arrival rate</i>	0.072	15.1
<i>C</i>	<i>Pilot / Tugboat</i>	0.17	83.15
<i>D</i>	<i>Current profile</i>	0.008	0.17
<i>F</i>	<i>Pursuit distance</i>	0.018	0.91
<i>AC</i>	<i>Arrival rate - Pilot / Tugboat</i>	0.008	0.19
<i>AF</i>	<i>Arrival rate - Pursuit distance</i>	0.003	0.02

The pilot / tugboat availability and the arrival rate are the most evident factors affecting the tugboat utilization. This is natural since, when there is scarcity in the resource or when the demand is increased the utilization increases.

The current profile and the pursuit distance have indirect influence on the tugboat utilization through their effect on the transit time. High level of the current profile and longer pursuit distances increase the transit time and thus increases the tugboat utilization.

The other weak but significant effects are the arrival rate and the pilot / tugboat interaction and the arrival rate and the pursuit distance interaction. The effects of the pilot / tugboat availability and the pursuit distance are more serious when the arrival rate is high.

6.3. Summary of Factor Effects

According to the results of the simulation experiments, each factor has an importance on different aspects. However, the arrival rate and the pilot / tugboat availability factors dominate other factors in most of the responses.

The arrival rate preforms the total number of vessels passed and thus, controls the vessel density in the Strait as well. Besides, the arrival rate is the principal factor on the number of vessels in queues, hence, mostly affecting the average and maximum waiting times of the vessels. Besides, transit times, pilot and tugboat utilizations are also affected considerably by the arrival rate.

The pilot / tugboat availability is the second important factor on the average and maximum waiting times of the vessels and in this respect on the number vessels in the

queues. In addition, the pilot / tugboat levels clearly govern the pilot and tugboat utilizations.

The pursuit distance has the major influence on transit times of vessels since it is an important parameter regarding overtaking conditions, which is highly influential on the transit times of vessels. Accordingly, this factor has an important effect on the vessel density in the Strait, the number of vessels in queues and the average waiting time of vessels. Furthermore, it also has a significant effect on the maximum waiting time, and the pilot and tugboat utilizations.

The vessel profile is mostly influential on the average and maximum waiting times and thus, on the number of vessels in queues as well. However, since hazardous cargo carrying vessels do not require additional support services, vessel profile do not affect the pilot and tugboat utilizations. Besides, this factor in itself does not imply additional vessel arrivals to the system, so it does not have any effect on the number of vessels passed or the vessel density in the Strait.

The seasons have serious effects on the average and maximum waiting times of vessels and the number of vessels in queues, since visibility effect is also observed through this factor. In this respect, it also has significant but very slight effect on the number of vessels passed. However, it does not affect the transit times, the vessel density in the Strait or the pilot and the tugboat utilizations.

The current profile has important effects on the transit time of vessels and on the maximum waiting time. Consequently, this factor exhibit significant effects on the other performance measures as well.

Lastly, the Kandilli region encounter prevention rule has significant but minor effects (compared to the other factors) on the average waiting times of vessels and the number of vessels in queues. However, it does not have significant effects on the other performance measures.

The scenario analysis also exhibits interesting relationships among factors. The arrival rate and the pilot / tugboat availability interaction (AC) has serious effects on all of the responses, especially on the average and maximum waiting times of vessels and the number of vessels in queues. This interaction is at least as important as the vessel profile and the pursuit distance factors. On the other hand, the three-way interaction of the arrival rate, the pilot/ tugboat availability and the season (ACG) also has quite important effects on the same responses.

Since the arrival rate is the dominant factor on the system, its interaction with other factors, such as the vessel profile, the current profile, the pursuit distance and the season have some significant but minor effects on some of the responses. The arrival rate and the pursuit distance interaction (AF) affects transit times and vessel density, whereas the arrival rate and the current profile interaction (AD) has influence on the maximum waiting time.

In addition, the interactions of pursuit distance, vessel profile and season with the second dominant factor of pilot / tugboat availability also has weak effects on the transit times and waiting times especially.

6.4. Comparison of Scenario Outputs

In this section, some of the selected scenario outputs are compared to enhance the understanding of factors' effects on the simulation results and to reveal some interesting implications of the model solutions.

In the scenario analysis, 64 simulation runs with 10 replications (corresponding to the 64 combinations of considered factors) are taken into consideration based on a 2^{7-1} fractional factorial design. A full factorial design with $k=7$ factors each at only two levels would have required $2^k = 128$ runs. That is, simulation experiments are based one-half fraction of the full design and for each scenario run at least two of the factors' levels are changed. Therefore, some of the possible scenarios (that could be constituted with single factor level change) are not included in the design.

In Table 6.13, the scenarios with base, best and worst factor settings are displayed. The results of the simulation runs with these settings are displayed in Table 6.14. The scenarios with the base and the overall best settings do not take part in the scenario analysis through fractional factorial design, while the overall worst setting scenario is the scenario 64 (see Appendix C).

Table 6.13. Scenarios with base, best and worst settings

<i>Factor</i>	<i>Name</i>	<i>Base</i>	<i>Best</i>	<i>Worst</i>
<i>A</i>	<i>Arrival Rate</i>	Normal	Normal	High
<i>B</i>	<i>Vessel Profile</i>	Normal	Normal	HazMat High
<i>C</i>	<i>Pilot/Tugboat</i>	15/9	20/9	15/6
<i>D</i>	<i>Current Profile</i>	Normal	Normal	High
<i>E</i>	<i>Kandilli Rule</i>	Conservative	Normal	Conservative
<i>F</i>	<i>Pursuit Distance</i>	8 cables	4 cables	8 cables
<i>G</i>	<i>Season</i>	Winter	Summer	Winter

Table 6.14. Comparison of scenarios with base, best and worst settings (for 4 months)

<i>Scenario</i>	<i>No of Vessels Passed</i>	<i>Avg Transit (minutes)</i>	<i>Avg Waiting (minutes)</i>	<i>Max Waiting (minutes)</i>	<i>No in Queues</i>	<i>Density in the Strait</i>	<i>Pilot Utilization</i>	<i>Tugboat Utilization</i>
<i>Base</i>	18034	102.1	425.6	13474.1	35.2	0.635	0.298	0.500
<i>Best</i>	18037	98.5	120.4	4166.2	11.5	0.612	0.216	0.325
<i>Worst</i>	20879	105.4	1779.6	122301.5	201.0	0.758	0.353	0.584

According to results given in Table 6.14, the average waiting times of vessels vary between 120 minutes and 1780 minutes. The average numbers of vessels in queues are between 11.5 and 201. This variation in the outputs indicates the importance of the selected factors on the performance measures. The number of vessels basically changes with the arrival rate, so the number of vessel in the base scenario and the best scenario do not vary. In this respect, the vessel density in the Strait does not change too much. Pilot and tugboat utilizations mostly depend on the pilot / tugboat availability, thus the base and the worst scenario results are less varied in this regard.

The base scenario with the above settings is then compared with some selected scenarios from the simulation experiments in a way to represent a single factor level change. Related results are displayed in Table 6.15. For instance, the scenario 54 is different than the factor settings of the base scenario just in the arrival rate setting (which is set to high).

Table 6.15. Comparison of selected scenarios through single factor change (for 4 months)

Scenario No	Factor Change	No of Vessels Passed	Avg Transit	Avg Waiting	Max Waiting	No in Queues	Density in the Strait	Pilot Utilization	Tugboat Utilization
Base		18034	102.1	425.6	13474.1	35.2	0.635	0.298	0.500
54	Arrival (High)	20990	103.8	1334.4	74256.4	131.5	0.751	0.351	0.583
55	Vessel Profile (HazMat High)	17982	102.3	791.7	33920.8	60.6	0.634	0.297	0.496
49	Pilot / Tugboat (20/9)	18037	102.6	236.7	7175.0	20.5	0.638	0.225	0.338
61	Current (High)	18032	103.8	521.0	19835.5	40.6	0.645	0.303	0.510
37	Kandilli Rule (Normal)	18039	102.2	407.0	14079.3	33.6	0.635	0.299	0.501
21	Pursuit (4 cables)	18040	98.4	369.1	13565.9	29.8	0.611	0.287	0.484
53	Season (Summer)	18045	102.2	272.1	5732.1	26.4	0.635	0.298	0.501

Through Table 6.15, the effect of a single factor change on the performance measures can easily be followed. If for example, the arrival rate were to be 15 per cent higher than the normal setting, than the average waiting time would be three times higher than the base case. In this case, the number in the queues would also be nearly four times higher than the base case; in addition the vessel density in the Strait would increase about 12 per cent.

The vessel profile change would affect the waiting times and the number in the queues especially. The average waiting time and the number in the queues would increase about two times if the hazardous material carrying vessels increase from 1.5 per cent in total vessels to 9.4 per cent in total vessels (see Table 6.2).

On the other hand, the pilot / tugboat availability increase would decrease the average waiting times and the number of vessels in the queues about 45 per cent. However, the utilizations would be clearly decreased.

The current profile increase would have influence on the transit times, waiting times and density in the Strait as well.

The Kandilli encounter prevention rule has the minimum effect on the system among all factors. A relaxation in the rule would cause minor decrease in the waiting times and in the queues.

The decrease in the pursuit distance would cause a significant decrease in the transit times of vessels through facilitating the overtaking in the Strait. In this respect, the waiting times, the number in the queues and the density in the Strait would directly be affected.

The season has quite an important effect on the waiting times and thus, number of vessels in the queues through visibility conditions. The change of season to summer would decrease the average waiting times about 35 per cent. In this respect, the maximum waiting times would also be seriously decreased.

An interesting case would be to investigate scenario no 54 which involves a 15 per cent increase in the arrival rate of the base scenario which was given in Table 6.15. When the arrival rate setting of the base scenario is changed to high, the waiting time and other factors are seriously affected. In Table 6.16, selected scenarios from the simulation experiments are emphasized to demonstrate how the controllable factors of the pilot / tugboat availability, the Kandilli rule and the pursuit distance have influence in this case. In the scenarios displayed in Table 6.16, the vessel profile, the current and the season settings are kept fixed at the base scenario settings and the arrival rate is kept fixed at the high setting.

Table 6.16. Comparison of selected scenarios when the arrival rate is set to ‘High’
(for 4 months)

Scenario No	C: Pilot / TugBoat	E: Kandilli	F: Pursuit	No of Vessels Passed	Avg Transit	Avg Waiting	Max Waiting	No in Queues	Density in the Strait	Pilot Utilization	Tugboat Utilization
54	15/6	Conservative	8 cables	20990	103.8	1334.4	74256.4	131.5	0.751	0.351	0.583
6	15/6	Normal	4 cables	21047	99.3	1077.4	63060.0	98.6	0.720	0.336	0.562
34	20/9	Normal	8 cables	21165	104.6	615.7	20598.1	51.0	0.763	0.269	0.404
18	20/9	Conservative	4 cables	21181	99.8	518.6	18949.8	41.8	0.728	0.257	0.386

As can be seen from Table 6.16, the change in the pilot / tugboat availability and the pursuit distance seems to be affective in decreasing the waiting times. However, the average waiting time is still 22 per cent higher than the average waiting time of the base scenario.

The simulation experiment outputs of the 64 scenarios with 10 replications are displayed in detail in Appendix C.

7. CONCLUSION

In this study, an integrated simulation model, which mimics the functioning of the transit maritime traffic in the Strait of Istanbul is presented. The model aimed to address the major components affecting the system. In this respect, the simulation model is equipped with a comprehensive arrival process model of the transit vessels, a stochastic treatment of the visibility issues and a stochastic treatment of the current issues. Traffic Rules and Regulations in progress in the Strait of Istanbul, the available pilotage and tugboat services, traffic lanes and overtaking conditions are all included in the model as well.

Consequently, the study elaborated on realistic representation of the random vessel arrivals, treatment of visibility issues and treatment of current issues in the Strait of Istanbul, through compilation and analysis of comprehensive data. In addition, due emphasis is given to adaptive and parametric modeling of lane structures and flow of transit traffic, as well as to the Strait Rules and Regulations governing the entrance and flow of transit vessels at the Strait of Istanbul.

The model is also intended to facilitate the development and analysis of realistic scenarios concerning the effects of type and frequency of transit vessels, availability of support services, interpretation of the Strait Regulations and environmental and meteorological conditions.

Accordingly, simulation experiments have been conducted through a fractional factorial design to specifically investigate the effects of factors of vessel arrival rates, vessel profiles, pilot and tugboat availabilities, current conditions, pursuit distances between vessels, seasons to represent visibility conditions on the performance measures. In addition, selected scenario outputs are also discussed to reveal the effects of important factors.

According to the results of the base scenario, the average number of vessels passing through the Strait is found 18,034 in four winter months. In this case, the average waiting time of vessels is 425.6 minutes, the average number of vessels waiting in the queues is 35 and the average transit time is 102,1 minutes. When the arrival rate is 15 per cent higher than the current (normal) state in the Strait, the average number of vessels passing through the Strait is found 20,990 in four winter months. This time, the average waiting time of vessels would be 1,334.4 minutes, the average number of vessels waiting in the queues would be 132 and the transit time is 103.8 minutes.

The scenario analysis also demonstrated that, if the pilot/tugboat availability is increased by 40 per cent and in addition the Kandilli encounter prevention rule applied liberally, the average waiting time and the number of vessels in queues would be decreased by 54 per cent and by 61 per cent respectively. Alternatively, if the pilot/tugboat availability is increased by 40 per cent and concurrently the pursuit distance between vessels is reduced by 50 per cent, the average waiting time and the number of vessels in queues would be decreased by 61 per cent and by 68 per cent respectively.

The results of the simulation experiments disclose the importance of each factor on different aspects. However, the arrival rate of transit vessels to the Strait and the pilot / tugboat availability in the system prevail against other factors in most of the performance measures. The arrival rate and pilot / tugboat availability highly influence the number of vessels waiting in queues and the average and maximum waiting times of vessels. In addition, arrival rate preforms the number of vessels passed and thus, the vessel density in the Strait.

The average transit time of vessels is mostly controlled by the pursuit distance and the current profile in the Strait. In this respect pursuit distance and current profile have significant effects on other outputs as well.

The vessel profile and season are quite effective on the average and maximum waiting time of vessels and accordingly on the number of vessels in the queues. On the other hand, Kandilli encounter prevention rule has minor effects compared to other dominant factors.

Additionally, the simulation experiments revealed interesting interactions of factors. Arrival rate, pilot / tugboat availability and season interact on two-way and three-way among each other. Especially, arrival rate and pilot / tugboat availability interaction is quite serious than other factors on some performance measures. This relation points out to potential dramatic increases in queue lengths, in case of prospective increases of vessel arrivals at the Strait of Istanbul, in the insufficiency of support services.

The results of the study exhibit that a moderate increase in the transit vessel demand or a possible vessel profile alteration, in the existing states of support services and in the very possible adverse meteorological conditions could lead to very undesirable traffic congestions and thus to major increase in the 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.

7.1. Further Studies

In the Strait of Istanbul maritime traffic simulation model, the current Strait Traffic Rules and Regulations, transit vessel arrivals and characteristics, pilotage and tugboat services, meteorological, geographical and seasonal conditions are considered to provide a platform to analyze the effectiveness of various policies and decisions related to the transit traffic in the Strait of Istanbul.

Apart from those major factors affecting the transit traffic in the Strait, there are some other factors which have been held beyond the scope of this study. Maritime accident occurrences and local traffic activities in the Strait of Istanbul has influence on the transit traffic. Furthermore, meteorological conditions, especially major storms, in the Black Sea region also influence the Strait through affecting vessel arrival patterns and Strait entrance priorities. These situations that are not addressed in the current model can be analyzed and integrated to an expanded model.

As mentioned before, the Strait simulation model has various simplifications and assumptions on the real system. Essentially, the primary Strait Regulations are applied in the simulation model, but the minor details of the Strait entrance procedures and possible

interpretations of the Regulations (especially the issues and decisions open to judgment and intuition) are not aimed to be represented. Accordingly, a precise decision flow of the Strait Authority on the entrance procedures can be mapped and integrated to the simulation model in a further study.

This study of simulation modeling of the transit maritime traffic in the Strait of Istanbul is conducted under the research project on the comprehensive risk management and analysis of the Strait of Istanbul with cooperation of Rutgers University and Boğaziçi University through the supports of NSF (National Science Foundation) and TÜBİTAK (Turkish Technological and Scientific Research Institute). Consequently, the knowledge base and the results of this study will support, and the simulation model developed is expected to provide the required infrastructure and the basis to a further risk management study of the Strait of Istanbul.

APPENDIX A: ARRIVAL PROCESS PROBABILITY DISTRIBUTIONS

Table A.1. Fitted distributions to vessel clusters in arrival processes

Number of data points	Vessel type	Length	Direction	Distribution expression	Square error	Chi-square P-value
246	Gen Cargo	0-50	N-S	EXPO(2.12e+003)	0.0018	0.495
236	Gen Cargo	0-50	S-N	WEIB(2.27e+003, 1.07)	0.0031	0.478
8461	Gen Cargo	50-100	N-S	-0.001 + GAMM(72.6, 0.855)	0.0010	< 0.005
8439	Gen Cargo	50-100	S-N	-0.001 + GAMM(68.5, 0.912)	0.0001	< 0.005
9829	Gen Cargo	100-150	N-S	-0.001 + WEIB(48.9, 0.915)	0.0001	< 0.005
9659	Gen Cargo	100-150	S-N	-0.001 + GAMM(58.8, 0.927)	0.0003	< 0.005
2401	Gen Cargo	150-200	N-S	GAMM(258, 0.848)	0.0011	< 0.005
2394	Gen Cargo	150-200	S-N	GAMM(254, 0.866)	0.0005	0.0111
585	Gen Cargo	200-250	N-S	1 + 5.55e+003 * BETA(0.712, 3.4)	0.0015	0.0788
582	Gen Cargo	200-250	S-N	5.26e+003 * BETA(0.589, 2.86)	0.0025	< 0.005
63	Gen Cargo	250-300	N-S	171 + 2.52e+004 * BETA(0.939, 1.99)	0.0074	0.132
54	Gen Cargo	250-300	S-N	3.35e+004 * BETA(0.689, 1.69)	0.0174	0.102
3	Tanker	0-50	N-S	UNIF(125246.5,181985.7)	-	-
2	Tanker	0-50	S-N	UNIF(226013.73,238013.73)	-	-
1347	Tanker	50-100	N-S	3.92e+003 * BETA(0.833, 7.34)	0.0007	0.142
1369	Tanker	50-100	S-N	GAMM(402, 0.955)	0.0003	0.416
1020	Tanker	100-150	N-S	3.8e+003 * BETA(0.682, 4.35)	0.0011	0.0391
1018	Tanker	100-150	S-N	GAMM(509, 1.01)	0.0005	0.714
1179	Tanker	150-200	N-S	-0.001 + 4.99e+003 * BETA(0.658, 6.72)	0.0009	0.293
1190	Tanker	150-200	S-N	LOGN(614, 1.77e+003)	0.0029	< 0.005
659	Tanker	200-250	N-S	7e+003 * BETA(0.74, 5.75)	0.0042	< 0.005
662	Tanker	200-250	S-N	6.79e+003 * BETA(0.602, 4.58)	0.0021	0.0135
356	Tanker	250-300	N-S	8.8e+003 * BETA(0.804, 3.6)	0.0070	< 0.005
356	Tanker	250-300	S-N	1 + 7.12e+003 * BETA(0.655, 2.52)	0.0039	0.071
1	HazMat	0-50	N-S	UNIF(200000,300000)	-	-
0	HazMat	0-50	S-N	-	-	-
140	HazMat	50-100	N-S	18 + EXPO(3.7e+003)	0.0029	> 0.75
85	HazMat	50-100	S-N	62 + 2.6e+004 * BETA(0.84, 2.73)	0.0019	0.711
100	HazMat	100-150	N-S	186 + WEIB(5.16e+003, 1.06)	0.0122	0.327
190	HazMat	100-150	S-N	1 + WEIB(2.79e+003, 1.06)	0.0026	0.249
131	HazMat	150-200	N-S	4 + GAMM(3.01e+003, 1.34)	0.0080	0.127
89	HazMat	150-200	S-N	8 + EXPO(5.87e+003)	0.0017	> 0.75
64	HazMat	200-250	N-S	351 + WEIB(7.93e+003, 1.1)	0.0076	0.144
31	HazMat	200-250	S-N	1.2e+003 + 3.51e+004 * BETA(0.884, 1.27)	0.0193	0.0817
3	HazMat	250-300	N-S	UNIF(86821.43,52905.56)	-	-
11	HazMat	250-300	S-N	UNIF(6.98e+003, 2.06e+005)	-	-
0	LNG-LPG	0-50	N-S	-	-	-
0	LNG-LPG	0-50	S-N	-	-	-
30	LNG-LPG	50-100	N-S	1.33e+003 + 6.2e+004 * BETA(0.842, 2.47)	0.0396	0.16
97	LNG-LPG	50-100	S-N	31 + WEIB(5.45e+003, 1.02)	0.0040	0.0913
13	LNG-LPG	100-150	N-S	UNIF(3.57e+003, 1.03e+005)	-	-
70	LNG-LPG	100-150	S-N	17 + 2.85e+004 * BETA(0.88, 2.59)	0.0070	0.189
2	LNG-LPG	150-200	N-S	UNIF(0,300000)	-	-
69	LNG-LPG	150-200	S-N	87 + 2.34e+004 * BETA(0.788, 1.7)	0.0037	0.684
4	LNG-LPG	200-250	N-S	UNIF(30000,110000)	-	-
47	LNG-LPG	200-250	S-N	118 + GAMM(1.44e+004, 0.753)	0.0019	0.224
0	LNG-LPG	250-300	N-S	-	-	-
0	LNG-LPG	250-300	S-N	-	-	-

Table A.2. Pilot demand, direct / indirect passing and anchoring frequencies of vessel clusters in arrival processes

<i>Vessel type</i>	<i>Length</i>	<i>Direction</i>	<i>Pilot demand rate</i>	<i>Direct pass rate</i>	<i>Anchoring rate</i>
<i>Gen Cargo</i>	<i>0-50</i>	<i>N-S</i>	0.252	0.354	0.028
<i>Gen Cargo</i>	<i>0-50</i>	<i>S-N</i>	0.157	0.419	0.178
<i>Gen Cargo</i>	<i>50-100</i>	<i>N-S</i>	0.248	0.385	0.013
<i>Gen Cargo</i>	<i>50-100</i>	<i>S-N</i>	0.279	0.380	0.381
<i>Gen Cargo</i>	<i>100-150</i>	<i>N-S</i>	0.352	0.372	0.005
<i>Gen Cargo</i>	<i>100-150</i>	<i>S-N</i>	0.387	0.383	0.398
<i>Gen Cargo</i>	<i>150-200</i>	<i>N-S</i>	0.764	0.386	0.002
<i>Gen Cargo</i>	<i>150-200</i>	<i>S-N</i>	0.769	0.366	0.161
<i>Gen Cargo</i>	<i>200-250</i>	<i>N-S</i>	0.921	0.391	0.002
<i>Gen Cargo</i>	<i>200-250</i>	<i>S-N</i>	0.912	0.381	0.088
<i>Gen Cargo</i>	<i>250-300</i>	<i>N-S</i>	0.937	0.444	0.000
<i>Gen Cargo</i>	<i>250-300</i>	<i>S-N</i>	0.981	0.426	0.037
<i>Tanker</i>	<i>0-50</i>	<i>N-S</i>	0.000	0.667	0.000
<i>Tanker</i>	<i>0-50</i>	<i>S-N</i>	0.000	0.000	0.000
<i>Tanker</i>	<i>50-100</i>	<i>N-S</i>	0.268	0.391	0.005
<i>Tanker</i>	<i>50-100</i>	<i>S-N</i>	0.291	0.395	0.364
<i>Tanker</i>	<i>100-150</i>	<i>N-S</i>	0.483	0.338	0.001
<i>Tanker</i>	<i>100-150</i>	<i>S-N</i>	0.494	0.383	0.414
<i>Tanker</i>	<i>150-200</i>	<i>N-S</i>	0.913	0.366	0.001
<i>Tanker</i>	<i>150-200</i>	<i>S-N</i>	0.939	0.393	0.192
<i>Tanker</i>	<i>200-250</i>	<i>N-S</i>	0.959	0.392	0.002
<i>Tanker</i>	<i>200-250</i>	<i>S-N</i>	0.979	0.384	0.097
<i>Tanker</i>	<i>250-300</i>	<i>N-S</i>	0.975	0.346	0.003
<i>Tanker</i>	<i>250-300</i>	<i>S-N</i>	0.975	0.351	0.087
<i>HazMat</i>	<i>0-50</i>	<i>N-S</i>	0.000	0.000	0.000
<i>HazMat</i>	<i>0-50</i>	<i>S-N</i>	-	-	-
<i>HazMat</i>	<i>50-100</i>	<i>N-S</i>	0.443	0.343	0.007
<i>HazMat</i>	<i>50-100</i>	<i>S-N</i>	0.600	0.329	0.353
<i>HazMat</i>	<i>100-150</i>	<i>N-S</i>	0.560	0.320	0.010
<i>HazMat</i>	<i>100-150</i>	<i>S-N</i>	0.568	0.389	0.105
<i>HazMat</i>	<i>150-200</i>	<i>N-S</i>	0.908	0.374	0.000
<i>HazMat</i>	<i>150-200</i>	<i>S-N</i>	0.787	0.348	0.022
<i>HazMat</i>	<i>200-250</i>	<i>N-S</i>	1.000	0.375	0.000
<i>HazMat</i>	<i>200-250</i>	<i>S-N</i>	0.968	0.419	0.032
<i>HazMat</i>	<i>250-300</i>	<i>N-S</i>	1.000	0.333	0.000
<i>HazMat</i>	<i>250-300</i>	<i>S-N</i>	1.000	0.364	0.091
<i>LNG-LPG</i>	<i>0-50</i>	<i>N-S</i>	-	-	-
<i>LNG-LPG</i>	<i>0-50</i>	<i>S-N</i>	-	-	-
<i>LNG-LPG</i>	<i>50-100</i>	<i>N-S</i>	0.433	0.433	0.033
<i>LNG-LPG</i>	<i>50-100</i>	<i>S-N</i>	0.423	0.340	0.454
<i>LNG-LPG</i>	<i>100-150</i>	<i>N-S</i>	0.692	0.308	0.000
<i>LNG-LPG</i>	<i>100-150</i>	<i>S-N</i>	0.671	0.300	0.171
<i>LNG-LPG</i>	<i>150-200</i>	<i>N-S</i>	0.500	1.000	0.000
<i>LNG-LPG</i>	<i>150-200</i>	<i>S-N</i>	0.971	0.362	0.203
<i>LNG-LPG</i>	<i>200-250</i>	<i>N-S</i>	1.000	0.250	0.000
<i>LNG-LPG</i>	<i>200-250</i>	<i>S-N</i>	1.000	0.404	0.085
<i>LNG-LPG</i>	<i>250-300</i>	<i>N-S</i>	-	-	-
<i>LNG-LPG</i>	<i>250-300</i>	<i>S-N</i>	-	-	-

Table A.3. Fitted distributions to passenger vessels in arrival processes

Number of data points	Vessel type	Direct /		Distribution expression	Square error	Chi-square P-value
		Indirect / Naval	Direction			
410	Passenger	Direct	N-S	GAMM(1.72e+003,0.732)	0.0039	0.0326
243	Passenger	Indirect	N-S	- 0.001+ EXPO(2110)	0.0092	0.0405
451	Passenger	Direct	S-N	9540 * BETA(0.412,3.07)	0.0060	< 0.005
205	Passenger	Indirect	S-N	7 + EXPO(2490)	0.0031	0.0693
93	Passenger	Naval	N-S	1 + WEIB(2.72e+003, 0.45)	0.0041	< 0.005
90	Passenger	Naval	S-N	WEIB(2.65e+003, 0.441)	0.0033	< 0.005

Table A.4. Pilot demand, direct / indirect passing and anchoring frequencies of passenger vessels in arrival processes

Vessel type	Direct /		Pilot demand rate	Direct pass rate	Anchoring rate
	Indirect / Naval	Direction			
Passenger	Direct	N-S	0.983	1.000	0.005
Passenger	Indirect	N-S	0.971	0.000	0.000
Passenger	Direct	S-N	0.982	1.000	0.011
Passenger	Indirect	S-N	0.956	0.000	0.019
Passenger	Naval	N-S	0.223	0.287	0.000
Passenger	Naval	S-N	0.198	0.374	0.000

Table A.5. Speed distributions by vessel type and length (in knots)

Length (meter) / Type	Passenger	LNG-LPG	HazMat	Tanker	General Cargo
< 50	TRIA(9.17, 9.81, 12)	TRIA(6, 8.64, 12)	TRIA(6, 8.64, 12)	TRIA(6, 8.64, 12)	TRIA(6, 8.64, 12)
50 - 100	TRIA(7, 10, 14)	UNIF(8,14)	TRIA(7, 9, 15)	TRIA(6, 9.94, 15)	TRIA(6, 10.1, 13.5)
100 - 150	TRIA(9, 11.9, 17)	TRIA(10.1, 10.2, 15)	TRIA(8, 14.8, 18)	TRIA(8, 8.96, 15)	TRIA(7, 9.06, 14.5)
150 - 200	TRIA(11, 16, 19)	TRIA(10, 12.7, 17)	TRIA(10, 14.3, 16)	TRIA(8, 12.9, 16)	TRIA(9, 12, 15)
200 - 250	TRIA(11, 16, 19)	TRIA(12, 12.1, 14)	TRIA(10, 12.5, 18)	TRIA(9, 12.6, 15)	TRIA(9, 11.1, 18)
250 - 300	TRIA(11, 16, 19)	TRIA(12, 12.1, 14)	TRIA(10, 12.5, 18)	TRIA(10, 13.6, 17)	TRIA(9, 12.3, 18)

APPENDIX B: OUTPUTS OF SIMULATION EXPERIMENTS

Table B.1. Outputs of scenarios (1-32)

Scenario No	A: Arrival Rate	B: Vessel Profile	C: Pilot / TugBoat	D: Current Profile	E: Kandilli Rule	F: Pursuit Distance	G: Season	No of Vessels Passed	Avg Transit	Avg Waiting	Max Waiting	No in Queues	Density in the Strait	Pilot Utilization	Tugboat Utilization
1	Normal	Normal	20/9	Normal	Normal	4 cables	Winter	18037.5	98.7	184.1	6270.7	16.1	0.6135	0.2163	0.3251
2	High	Normal	20/9	Normal	Normal	4 cables	Summer	21185.9	99.8	186.2	4931.9	20.8	0.7285	0.2568	0.3861
3	Normal	HazMat	20/9	Normal	Normal	4 cables	Summer	18042.5	98.7	169.4	4779.5	16.0	0.6137	0.2165	0.3254
4	High	HazMat	20/9	Normal	Normal	4 cables	Winter	21144.4	99.8	806.4	29307.3	63.3	0.7270	0.2557	0.3835
5	Normal	Normal	15/6	Normal	Normal	4 cables	Summer	18044.5	98.3	203.6	4785.0	19.6	0.6111	0.2867	0.4842
6	High	Normal	15/6	Normal	Normal	4 cables	Winter	21047	99.3	1077.4	63060.0	98.6	0.7197	0.3355	0.5615
7	Normal	HazMat	15/6	Normal	Normal	4 cables	Winter	18010.7	98.5	605.7	25736.1	45.2	0.6111	0.2861	0.4814
8	High	HazMat	15/6	Normal	Normal	4 cables	Summer	21052	99.1	1429.6	92501.1	149.9	0.7189	0.3350	0.5609
9	Normal	Normal	20/9	High	Normal	4 cables	Summer	18039.9	99.9	135.7	9690.7	12.0	0.6210	0.2193	0.3308
10	High	Normal	20/9	High	Normal	4 cables	Winter	21178.2	101.3	503.8	17981.8	40.4	0.7390	0.2605	0.3923
11	Normal	HazMat	20/9	High	Normal	4 cables	Winter	18043.5	100.3	323.4	12181.4	24.4	0.6234	0.2200	0.3311
12	High	HazMat	20/9	High	Normal	4 cables	Summer	21196.2	101.6	354.8	12679.0	35.3	0.7420	0.2615	0.3933
13	Normal	Normal	15/6	High	Normal	4 cables	Winter	18035.5	99.8	396.3	16012.7	30.9	0.6199	0.2909	0.4912
14	High	Normal	15/6	High	Normal	4 cables	Summer	21102.1	100.5	1187.1	63433.1	110.3	0.7308	0.3418	0.5755
15	Normal	HazMat	15/6	High	Normal	4 cables	Summer	18046.9	100.0	371.8	11461.2	33.0	0.6216	0.2916	0.4927
16	High	HazMat	15/6	High	Normal	4 cables	Winter	20962.3	100.8	1469.6	100747.7	151.0	0.7279	0.3383	0.5644
17	Normal	Normal	20/9	Normal	Conservative	4 cables	Summer	18039.3	98.6	125.7	4227.1	12.0	0.6124	0.2161	0.3252
18	High	Normal	20/9	Normal	Conservative	4 cables	Winter	21180.9	99.8	518.6	18949.8	41.8	0.7280	0.2566	0.3855
19	Normal	HazMat	20/9	Normal	Conservative	4 cables	Winter	18041	98.9	289.8	9227.8	23.5	0.6147	0.2167	0.3255
20	High	HazMat	20/9	Normal	Conservative	4 cables	Summer	21193.2	100.1	311.7	8630.0	33.5	0.7307	0.2573	0.3861
21	Normal	Normal	15/6	Normal	Conservative	4 cables	Winter	18039.8	98.4	369.1	13565.9	29.8	0.6115	0.2868	0.4837
22	High	Normal	15/6	Normal	Conservative	4 cables	Summer	21113.5	99.1	1134.4	62812.2	107.0	0.7204	0.3369	0.5660
23	Normal	HazMat	15/6	Normal	Conservative	4 cables	Summer	18042.6	98.6	330.1	7471.9	31.3	0.6127	0.2872	0.4839
24	High	HazMat	15/6	Normal	Conservative	4 cables	Winter	20963.5	99.3	1428.1	99990.5	148.9	0.7169	0.3330	0.5547
25	Normal	Normal	20/9	High	Conservative	4 cables	Winter	18039.4	100.2	213.3	10130.1	17.4	0.6225	0.2198	0.3309
26	High	Normal	20/9	High	Conservative	4 cables	Summer	21185.7	101.4	213.5	10012.6	22.6	0.7399	0.2610	0.3932
27	Normal	HazMat	20/9	High	Conservative	4 cables	Summer	18042.6	100.3	209.3	10154.7	17.7	0.6232	0.2201	0.3315
28	High	HazMat	20/9	High	Conservative	4 cables	Winter	21123	101.4	981.9	35109.3	75.4	0.7377	0.2594	0.3903
29	Normal	Normal	15/6	High	Conservative	4 cables	Summer	18041	99.8	235.4	10140.6	21.6	0.6201	0.2912	0.4927
30	High	Normal	15/6	High	Conservative	4 cables	Winter	21023.9	100.7	1211.0	71281.8	113.8	0.7295	0.3402	0.5699
31	Normal	HazMat	15/6	High	Conservative	4 cables	Winter	17993.9	99.9	774.9	34453.3	56.0	0.6192	0.2898	0.4884
32	High	HazMat	15/6	High	Conservative	4 cables	Summer	21006.5	100.6	1536.0	104775.6	168.5	0.7280	0.3389	0.5677

Table B.2. Outputs of scenarios (33-64)

Scenario No	A: Arrival Rate	B: Vessel Profile	C: Pilot / TugBoat	D: Current Profile	E: Kandilli Rule	F: Pursuit Distance	G: Season	No of Vessels Passed	Avg Transit	Avg Waiting	Max Waiting	No in Queues	Density in the Strait	Pilot Utilization	Tugboat Utilization
33	Normal	Normal	20/9	Normal	Normal	8 cables	Summer	18043.3	102.4	148.7	4312.7	14.4	0.6362	0.2248	0.3375
34	High	Normal	20/9	Normal	Normal	8 cables	Winter	21165	104.6	615.7	20598.1	51.0	0.7626	0.2695	0.4042
35	Normal	HazMat	20/9	Normal	Normal	8 cables	Winter	18041.7	102.8	348.4	10008.7	28.4	0.6388	0.2256	0.3382
36	High	HazMat	20/9	Normal	Normal	8 cables	Summer	21191	105.2	449.2	11819.8	47.4	0.7682	0.2714	0.4065
37	Normal	Normal	15/6	Normal	Normal	8 cables	Winter	18039.1	102.2	407.0	14079.3	33.6	0.6352	0.2985	0.5006
38	High	Normal	15/6	Normal	Normal	8 cables	Summer	21092.9	103.6	1299.0	67613.0	127.8	0.7526	0.3526	0.5897
39	Normal	HazMat	15/6	Normal	Normal	8 cables	Summer	18036.9	102.5	429.2	8946.6	40.9	0.6367	0.2989	0.5007
40	High	HazMat	15/6	Normal	Normal	8 cables	Winter	20913.1	103.8	1637.0	109601.3	179.0	0.7477	0.3483	0.5753
41	Normal	Normal	20/9	High	Normal	8 cables	Winter	18034.7	104.2	247.6	10264.1	20.6	0.6475	0.2290	0.3445
42	High	Normal	20/9	High	Normal	8 cables	Summer	21189.9	106.7	277.7	10410.0	29.9	0.7790	0.2757	0.4143
43	Normal	HazMat	20/9	High	Normal	8 cables	Summer	18048	104.3	253.4	10329.0	22.1	0.6485	0.2292	0.3445
44	High	HazMat	20/9	High	Normal	8 cables	Winter	21104	106.3	1150.6	40736.2	92.3	0.7732	0.2726	0.4095
45	Normal	Normal	15/6	High	Normal	8 cables	Summer	18048.6	103.7	287.1	10280.4	26.8	0.6448	0.3033	0.5103
46	High	Normal	15/6	High	Normal	8 cables	Winter	20968.7	105.5	1414.5	79324.5	140.5	0.7623	0.3568	0.5918
47	Normal	HazMat	15/6	High	Normal	8 cables	Winter	17973.1	103.7	855.0	38956.5	64.2	0.6423	0.3010	0.5040
48	High	HazMat	15/6	High	Normal	8 cables	Summer	20947	105.3	1776.6	119221.1	206.5	0.7598	0.3547	0.5893
49	Normal	Normal	20/9	Normal	Conservative	8 cables	Winter	18037.2	102.6	236.7	7175.0	20.5	0.6378	0.2253	0.3380
50	High	Normal	20/9	Normal	Conservative	8 cables	Summer	21198.8	104.9	268.9	6491.4	30.0	0.7659	0.2707	0.4058
51	Normal	HazMat	20/9	Normal	Conservative	8 cables	Summer	18049.7	102.8	222.8	5032.6	21.2	0.6389	0.2256	0.3383
52	High	HazMat	20/9	Normal	Conservative	8 cables	Winter	21091.7	104.6	1109.3	42045.1	90.8	0.7600	0.2675	0.4006
53	Normal	Normal	15/6	Normal	Conservative	8 cables	Summer	18044.5	102.2	272.1	5732.1	26.4	0.6349	0.2982	0.5009
54	High	Normal	15/6	Normal	Conservative	8 cables	Winter	20989.5	103.8	1334.4	74256.4	131.5	0.7508	0.3507	0.5830
55	Normal	HazMat	15/6	Normal	Conservative	8 cables	Winter	17982.3	102.3	791.7	33920.8	60.6	0.6338	0.2969	0.4964
56	High	HazMat	15/6	Normal	Conservative	8 cables	Summer	20975	103.7	1713.6	113344.8	196.9	0.7489	0.3494	0.5797
57	Normal	Normal	20/9	High	Conservative	8 cables	Summer	18038.4	104.1	172.7	9799.2	15.7	0.6466	0.2288	0.3444
58	High	Normal	20/9	High	Conservative	8 cables	Winter	21143.6	106.3	761.8	25849.1	60.9	0.7741	0.2736	0.4118
59	Normal	HazMat	20/9	High	Conservative	8 cables	Winter	18042.3	104.5	446.7	13378.5	33.3	0.6494	0.2296	0.3450
60	High	HazMat	20/9	High	Conservative	8 cables	Summer	21200.9	107.1	597.7	16621.0	59.6	0.7818	0.2767	0.4162
61	Normal	Normal	15/6	High	Conservative	8 cables	Winter	18031.7	103.8	521.0	19835.5	40.6	0.6448	0.3032	0.5096
62	High	Normal	15/6	High	Conservative	8 cables	Summer	21037.7	105.2	1498.6	81480.3	151.8	0.7624	0.3575	0.5972
63	Normal	HazMat	15/6	High	Conservative	8 cables	Summer	18017.7	104.2	568.1	14856.4	51.5	0.6467	0.3040	0.5096
64	High	HazMat	15/6	High	Conservative	8 cables	Winter	20878.7	105.4	1779.6	122301.5	201.0	0.7583	0.3534	0.5839

APPENDIX C: ANOVA TABLES AND MODEL GRAPHS

Table C.1. ANOVA table for number of vessels passed

Source	Sum of Squares	df	Mean Square	F-Value	p-value (Prob > F)	
Model	1492474067.83	4	373118517.0	13983.99	< 0.0001	significant
A-Arrival Rate	1490108490.00	1	1490108490.0	55847.32	< 0.0001	
C-Pilot / TugBoat	1252452.10	1	1252452.1	46.94	< 0.0001	
G-Season	237853.51	1	237853.5	8.91	0.0029	
AC	875272.23	1	875272.2	32.80	< 0.0001	
Residual	16942961.14	635	26681.8			
Lack of Fit	717573.54	59	12162.3	0.43	0.9999	not significant
Pure Error	16225387.60	576	28169.1			
Cor Total	1509417028.98	639				
Std. Dev.	163.35		R-Squared	0.9888		
Mean	19559.93		Adj R-Squared	0.9887		
C.V. %	0.8351		Pred R-Squared	0.9886		
PRESS	17210829.90		Adeq Precision	220.17		

Design-Expert® Software

No of Vessels Passed

X1 = A: Arrival Rate

Actual Factors

B: Vessel Profile = Normal

C: Pilot / TugBoat = 15/6

D: Current Profile = 1.00

E: Kandilli Rule = 4

F: Pursuit Distance = 8

G: Season = Winter

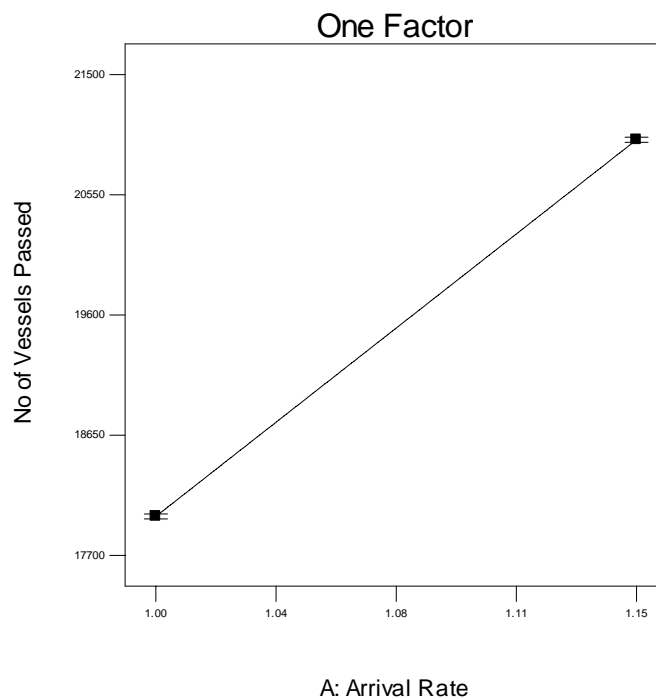


Figure C.1. Arrival rate effect on number of vessels passed

Design-Expert® Software

No of Vessels Passed

X1 = C: Pilot / TugBoat

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8
- G: Season = Winter

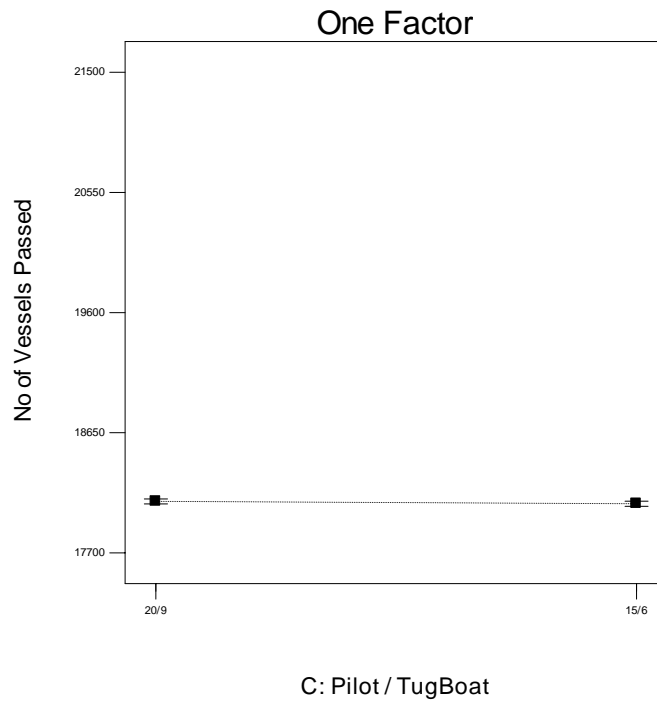


Figure C.2. Pilot / Tugboat effect on number of vessels passed

Design-Expert® Software

No of Vessels Passed

X1 = G: Season

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- C: Pilot / TugBoat = 15/6
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8

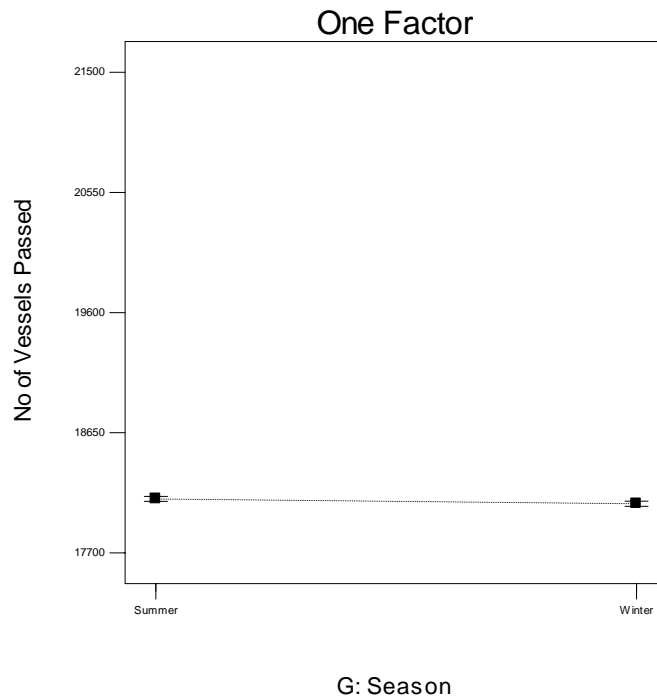


Figure C.3. Season effect on number of vessels passed

Design-Expert® Software

No of Vessels Passed

- C1 20/9
- ▲ C2 15/6

X1 = A: Arrival Rate
X2 = C: Pilot / TugBoat

Actual Factors
B: Vessel Profile = Normal
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter

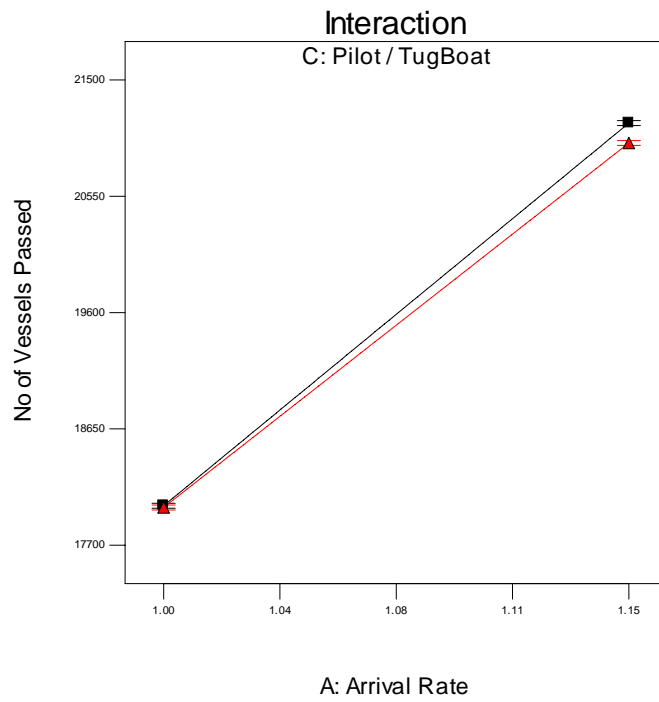


Figure C.4. Arrival rate – Pilot / Tugboat interaction effect on number of vessels passed

Table C.2. ANOVA table for average transit times of vessels

Source	Sum of Squares	df	Mean Square	F-Value	p-value (Prob > F)	
<i>Model</i>	3941.66	8	492.71	3881.04	< 0.0001	<i>significant</i>
<i>A-Arrival Rate</i>	322.65	1	322.65	2541.52	< 0.0001	
<i>B-Vessel Profile</i>	3.95	1	3.95	31.14	< 0.0001	
<i>C-Pilot / TugBoat</i>	67.09	1	67.09	528.50	< 0.0001	
<i>D-Current Profile</i>	392.35	1	392.35	3090.49	< 0.0001	
<i>F-Pursuit Distance</i>	3107.20	1	3107.20	24475.30	< 0.0001	
<i>AC</i>	14.68	1	14.68	115.66	< 0.0001	
<i>AF</i>	30.95	1	30.95	243.79	< 0.0001	
<i>CF</i>	2.78	1	2.78	21.90	< 0.0001	
<i>Residual</i>	80.11	631	0.13			
<i>Lack of Fit</i>	15.82	55	0.29	2.58	< 0.0001	<i>significant</i>
<i>Pure Error</i>	64.29	576	0.11			
<i>Cor Total</i>	4021.76	639				
<i>Std. Dev.</i>	0.3563		<i>R-Squared</i>	0.9801		
<i>Mean</i>	102.00		<i>Adj R-Squared</i>	0.9798		
<i>C.V. %</i>	0.3493		<i>Pred R-Squared</i>	0.9795		
<i>PRESS</i>	82.41		<i>Adeq Precision</i>	194.01		

Design-Expert® Software

Avg Transit

X1 = A: Arrival Rate

Actual Factors

B: Vessel Profile = Normal

C: Pilot / TugBoat = 15/6

D: Current Profile = 1.00

E: Kandilli Rule = 4

F: Pursuit Distance = 8

G: Season = Winter

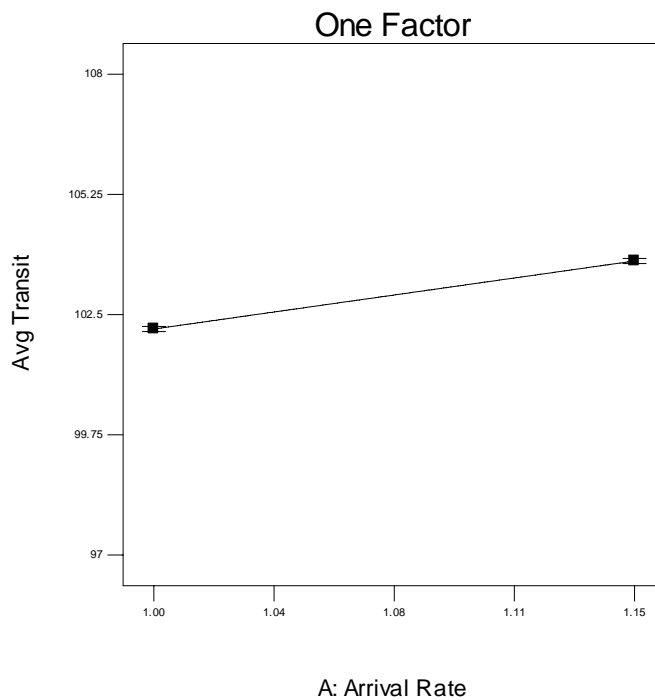


Figure C.5. Arrival rate effect on average transit times

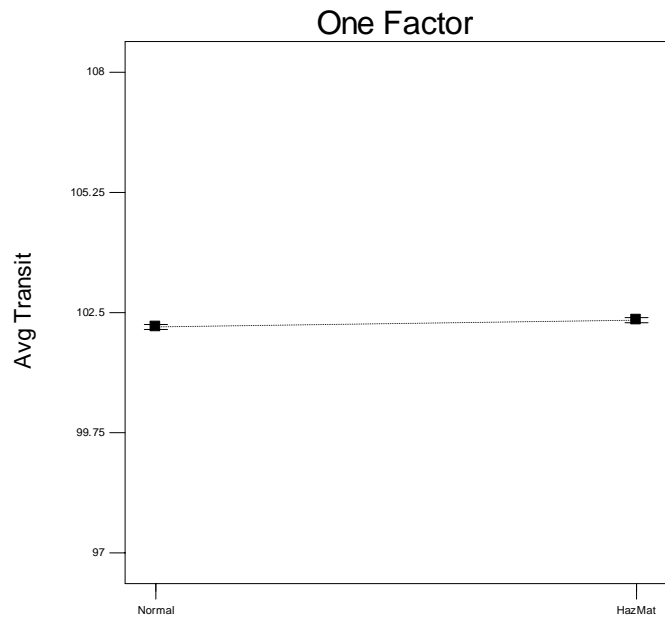
Design-Expert® Software

Avg Transit

X1 = B: Vessel Profile

Actual Factors

- A: Arrival Rate = 1.00
- C: Pilot / TugBoat = 15/6
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8
- G: Season = Winter



B: Vessel Profile

Figure C.6. Vessel profile effect on average transit times

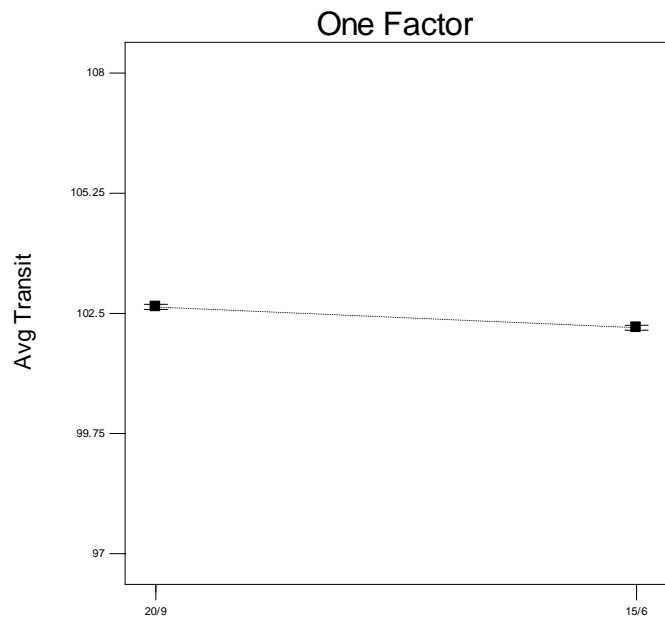
Design-Expert® Software

Avg Transit

X1 = C: Pilot / TugBoat

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8
- G: Season = Winter



C: Pilot / TugBoat

Figure C.7. Pilot / Tugboat effect on average transit times

Design-Expert® Software

Avg Transit

X1 = D: Current Profile

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- C: Pilot / TugBoat = 15/6
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8
- G: Season = Winter

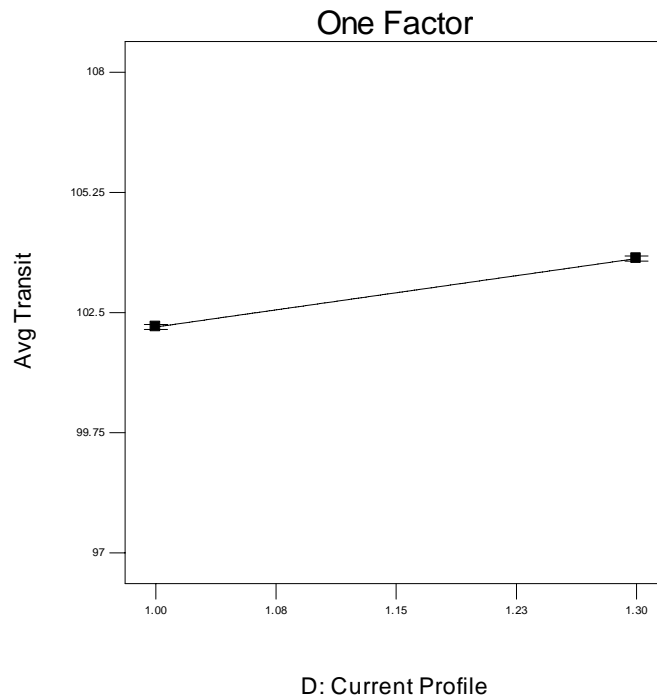


Figure C.8. Current profile effect on average transit times

Design-Expert® Software

Avg Transit

X1 = F: Pursuit Distance

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- C: Pilot / TugBoat = 15/6
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- G: Season = Winter

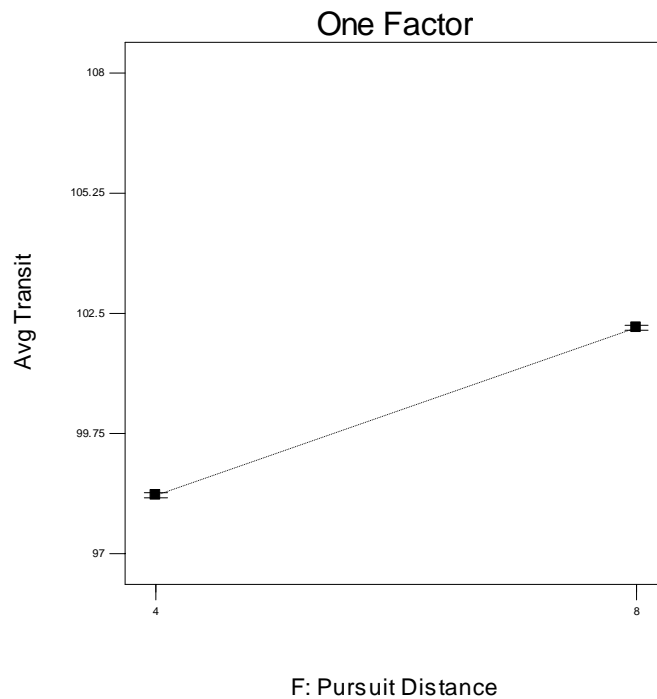


Figure C.9. Pursuit distance effect on average transit times

Design-Expert® Software

Avg Transit

- C1 20/9
- ▲ C2 15/6

X1 = A: Arrival Rate
X2 = C: Pilot / TugBoat

Actual Factors
B: Vessel Profile = Normal
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter

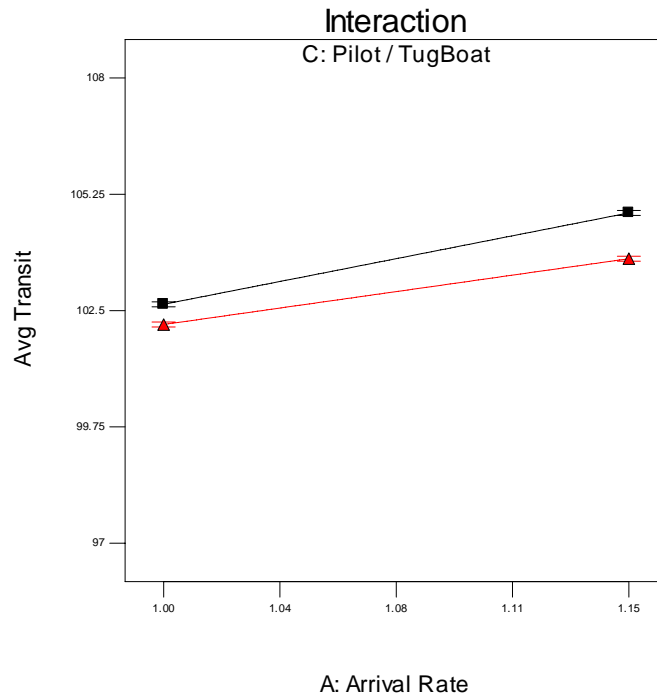


Figure C.10. Arrival rate – Pilot / Tugboat interaction effect on average transit times

Design-Expert® Software

Avg Transit

- F1 4
- ▲ F2 8

X1 = A: Arrival Rate
X2 = F: Pursuit Distance

Actual Factors
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
G: Season = Winter

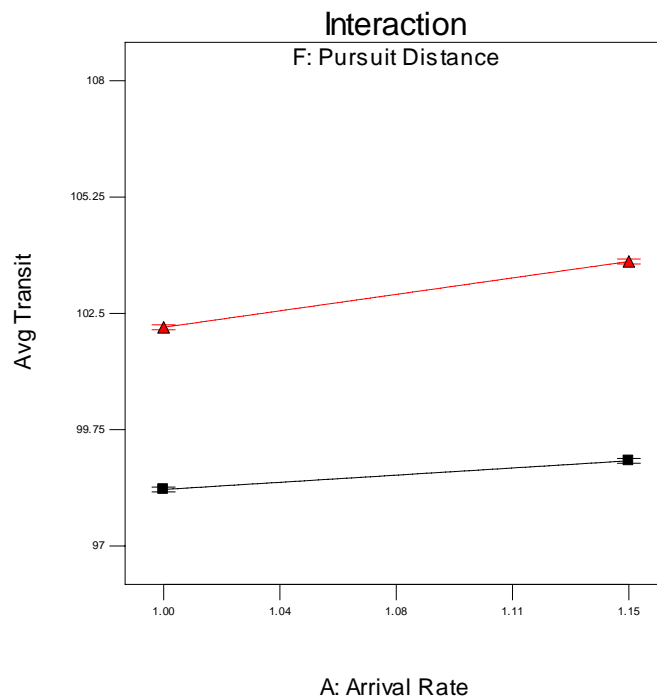


Figure C.11. Arrival rate – Pursuit distance interaction effect on average transit times

Design-Expert® Software

Avg Transit

■ F1 4

▲ F2 8

X1 = C: Pilot / TugBoat

X2 = F: Pursuit Distance

Actual Factors

A: Arrival Rate = 1.00

B: Vessel Profile = Normal

D: Current Profile = 1.00

E: Kandilli Rule = 4

G: Season = Winter

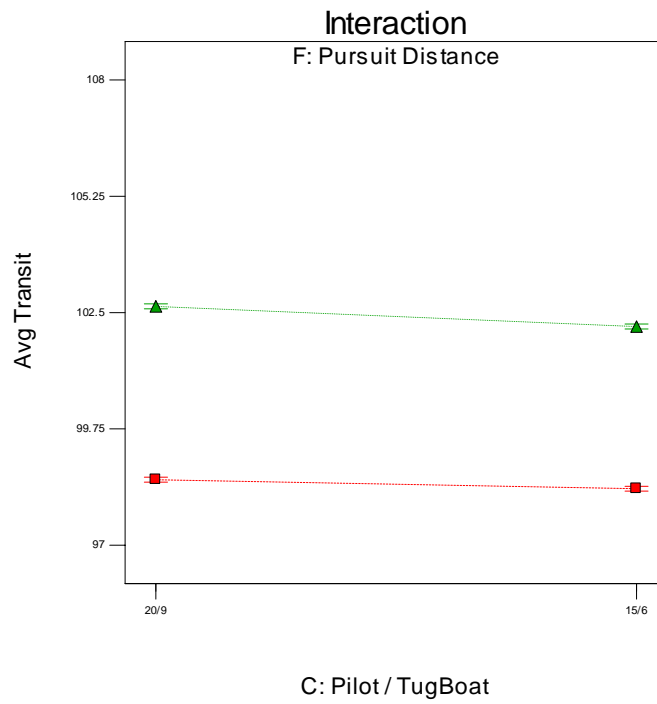


Figure C.12. Pilot / Tugboat – Pursuit distance interaction effect on average transit times

Table C.3. ANOVA table for average waiting times of vessels³

Source	Sum of Squares	df	Mean Square	F-Value	p-value (Prob > F)	
<i>Model</i>	385.26	14	27.52	1913.16	< 0.0001	<i>significant</i>
<i>A-Arrival Rate</i>	161.64	1	161.64	11237.38	< 0.0001	
<i>B-Vessel Profile</i>	30.73	1	30.73	2136.24	< 0.0001	
<i>C-Pilot / TugBoat</i>	118.37	1	118.37	8229.17	< 0.0001	
<i>D-Current Profile</i>	2.43	1	2.43	169.11	< 0.0001	
<i>E-Kandilli Rule</i>	0.57	1	0.57	39.69	< 0.0001	
<i>F-Pursuit Distance</i>	9.15	1	9.15	635.98	< 0.0001	
<i>G-Season</i>	35.60	1	35.60	2474.88	< 0.0001	
<i>AB</i>	0.34	1	0.34	23.71	< 0.0001	
<i>AC</i>	6.76	1	6.76	470.12	< 0.0001	
<i>AG</i>	0.15	1	0.15	10.18	0.0015	
<i>BC</i>	0.36	1	0.36	25.30	< 0.0001	
<i>CG</i>	6.64	1	6.64	461.91	< 0.0001	
<i>ABC</i>	2.05	1	2.05	142.25	< 0.0001	
<i>ACG</i>	10.48	1	10.48	728.31	< 0.0001	
<i>Residual</i>	8.99	625	0.01			
<i>Lack of Fit</i>	1.46	49	0.03	2.29	< 0.0001	<i>significant</i>
<i>Pure Error</i>	7.53	576	0.01			
<i>Cor Total</i>	394.25	639				
<i>Std. Dev.</i>	0.1199		<i>R-Squared</i>	0.9772		
<i>Mean</i>	6.22		<i>Adj R-Squared</i>	0.9767		
<i>C.V. %</i>	1.93		<i>Pred R-Squared</i>	0.9761		
<i>PRESS</i>	9.43		<i>Adeq Precision</i>	150.79		

Design-Expert® Software
Original Scale
Avg Waiting

X1 = A: Arrival Rate

Actual Factors
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter

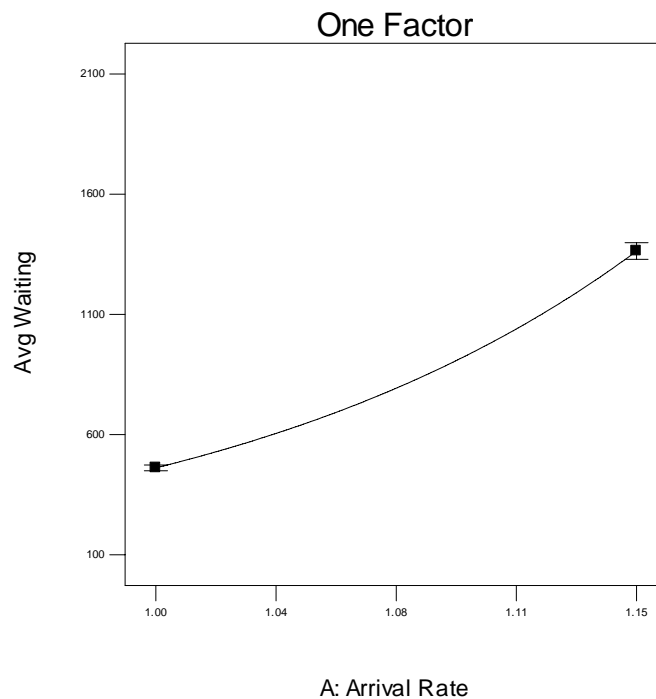


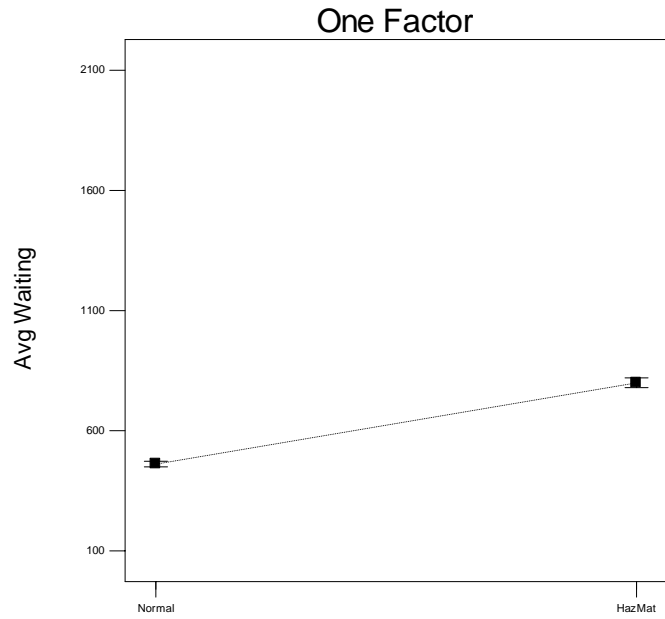
Figure C.13. Arrival rate effect on average waiting times

³ y' = $\ln y$ transformation is applied in the analysis of "Average waiting times of vessels" response.

Design-Expert® Software
Original Scale
Avg Waiting

X1 = B: Vessel Profile

Actual Factors
A: Arrival Rate = 1.00
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter



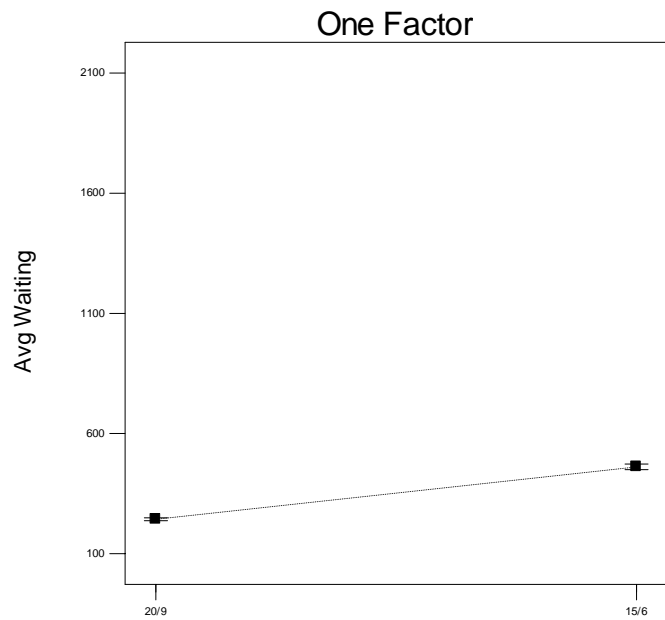
B: Vessel Profile

Figure C.14. Vessel profile effect on average waiting times

Design-Expert® Software
Original Scale
Avg Waiting

X1 = C: Pilot / TugBoat

Actual Factors
A: Arrival Rate = 1.00
B: Vessel Profile = Normal
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter



C: Pilot / TugBoat

Figure C.15. Pilot / Tugboat effect on average waiting times

Design-Expert® Software
Original Scale
Avg Waiting

X1 = D: Current Profile

Actual Factors
A: Arrival Rate = 1.00
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter

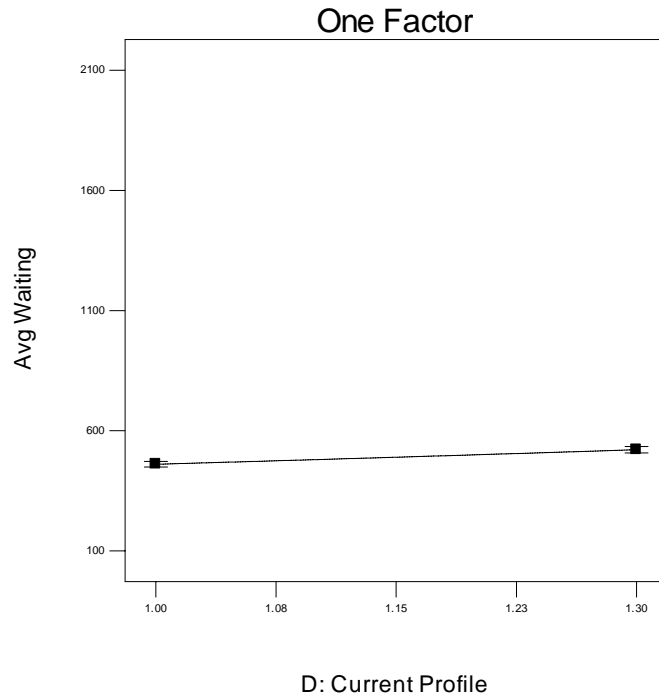


Figure C.16. Current profile effect on average waiting times

Design-Expert® Software
Original Scale
Avg Waiting

X1 = E: Kandilli Rule

Actual Factors
A: Arrival Rate = 1.00
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
F: Pursuit Distance = 8
G: Season = Winter

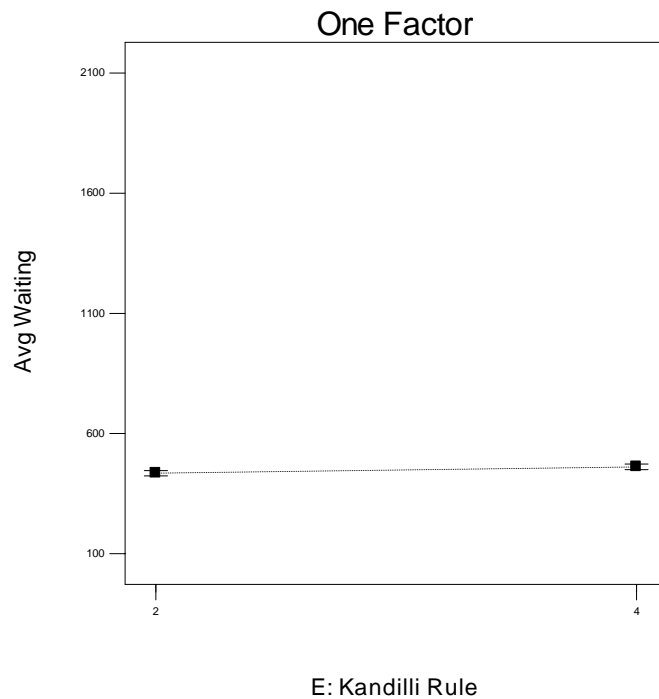


Figure C.17. Kandilli rule effect on average waiting times

Design-Expert® Software
Original Scale
Avg Waiting

X1 = F: Pursuit Distance

Actual Factors
A: Arrival Rate = 1.00
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
G: Season = Winter

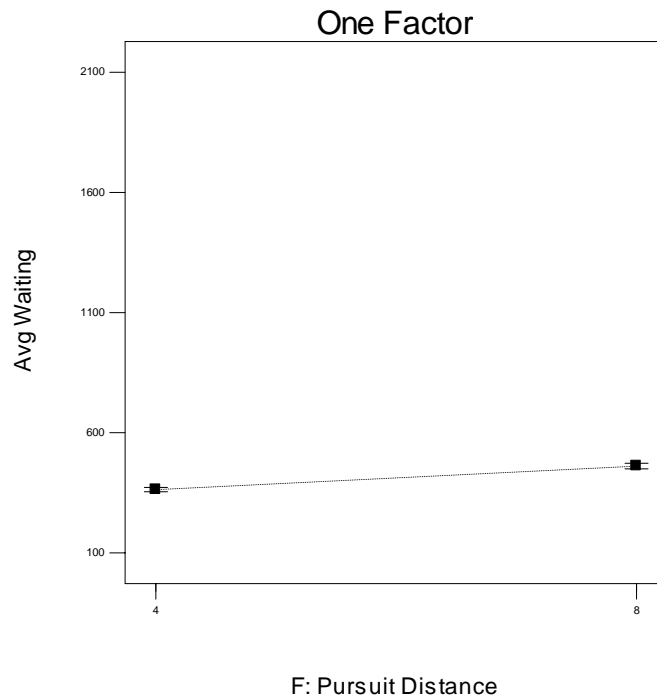


Figure C.18. Pursuit distance effect on average waiting times

Design-Expert® Software
Original Scale
Avg Waiting

X1 = G: Season

Actual Factors
A: Arrival Rate = 1.00
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8

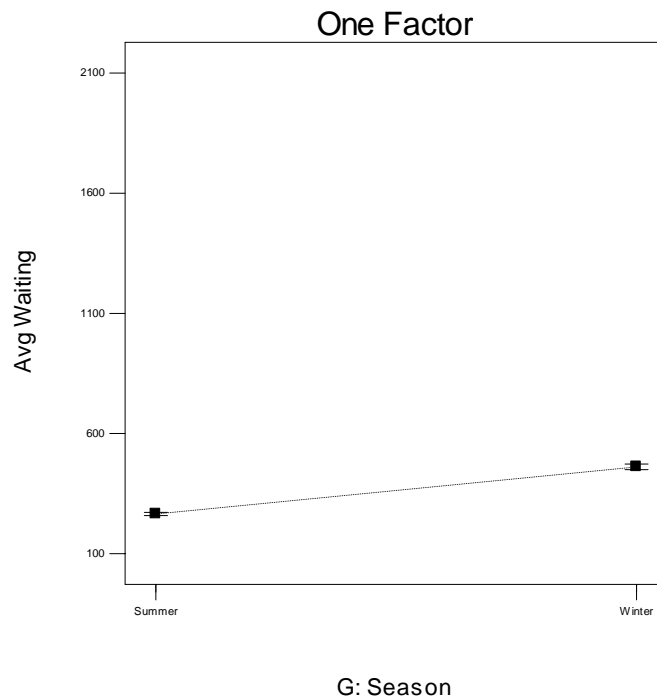


Figure C.19. Season effect on average waiting times

Design-Expert® Software
Original Scale
Avg Waiting

- B1 Normal
- ▲ B2 HazMat

X1 = A: Arrival Rate
X2 = B: Vessel Profile

Actual Factors
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter

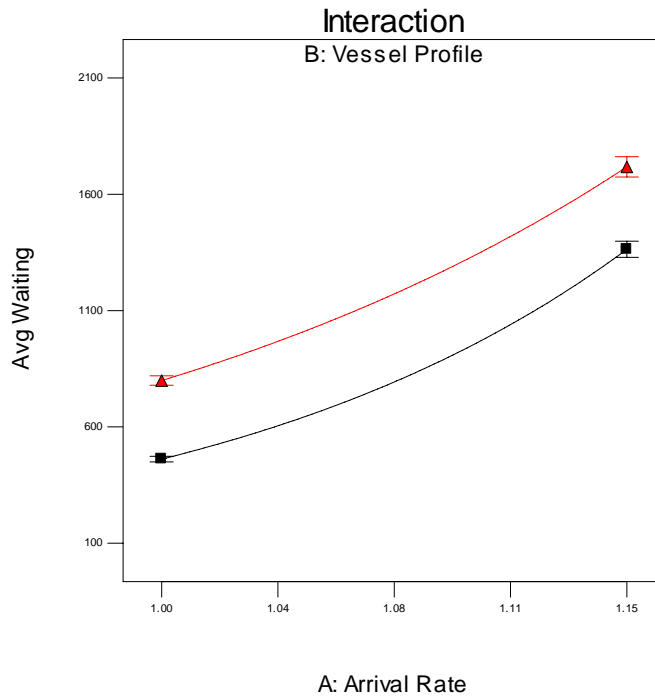


Figure C.20. Arrival rate - Vessel profile (when Pilot / Tugboat = 15/6) interaction effect on average waiting times

Design-Expert® Software
Original Scale
Avg Waiting

- B1 Normal
- ▲ B2 HazMat

X1 = A: Arrival Rate
X2 = B: Vessel Profile

Actual Factors
C: Pilot / TugBoat = 20/9
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter

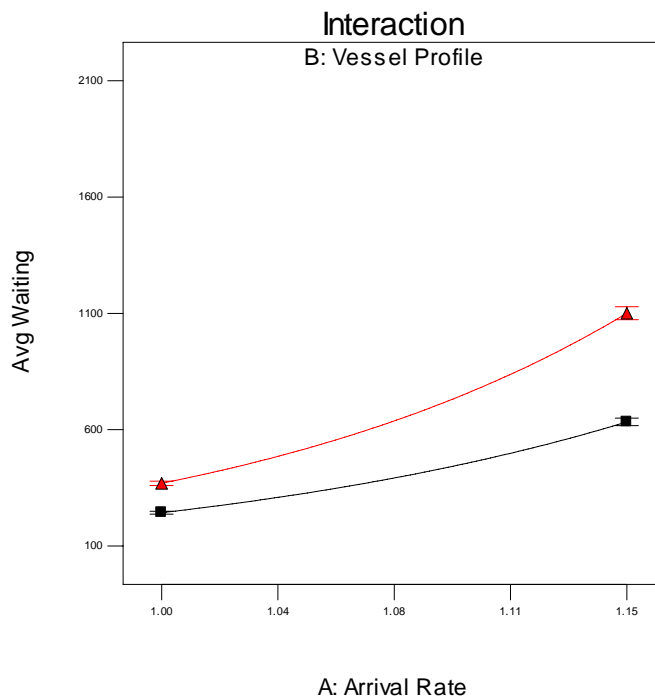


Figure C.21. Arrival rate - Vessel profile (when Pilot / Tugboat = 20/9) interaction effect on average waiting times

Design-Expert® Software
Original Scale
Avg Waiting

- C1 20/9
- ▲ C2 15/6

X1 = A: Arrival Rate
X2 = C: Pilot / TugBoat

Actual Factors
B: Vessel Profile = Normal
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter

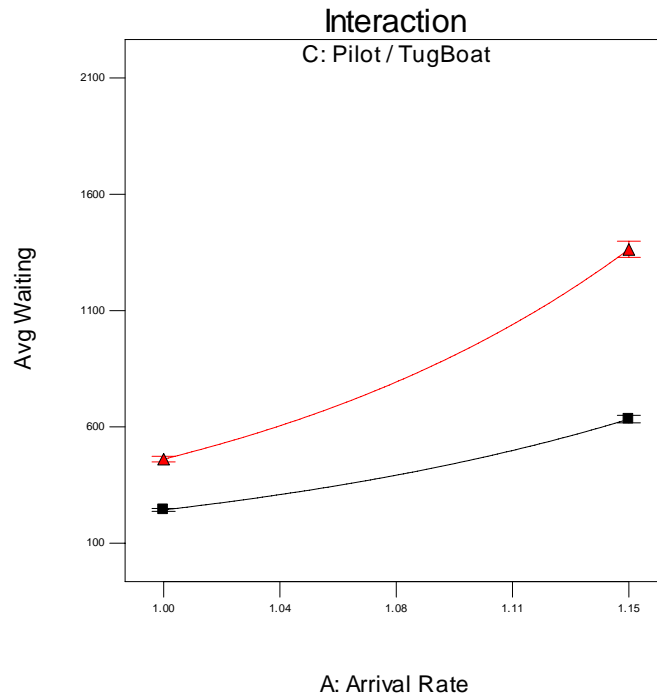


Figure C.22. Arrival rate - Pilot / Tugboat (when Season = winter) interaction effect on average waiting times

Design-Expert® Software
Original Scale
Avg Waiting

- C1 20/9
- ▲ C2 15/6

X1 = A: Arrival Rate
X2 = C: Pilot / TugBoat

Actual Factors
B: Vessel Profile = Normal
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Summer

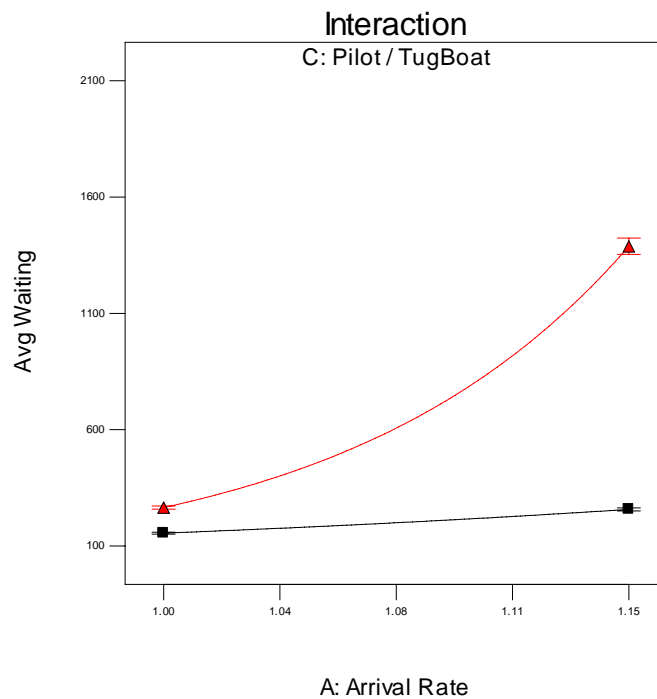


Figure C.23. Arrival rate - Pilot / Tugboat (when Season = summer) interaction effect on average waiting times

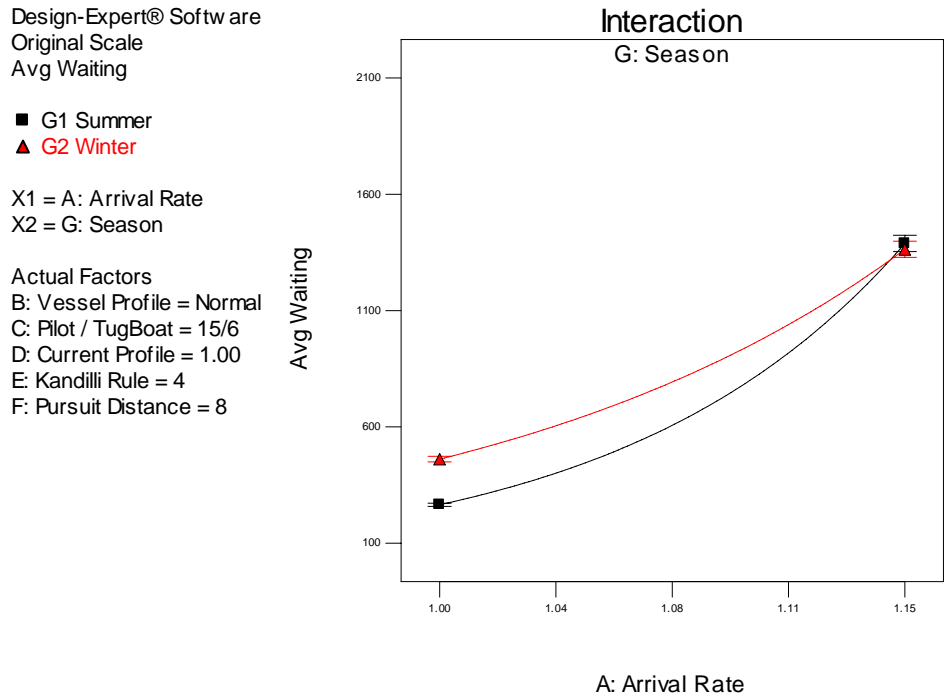


Figure C.24. Arrival rate – Season interaction effect on average waiting times

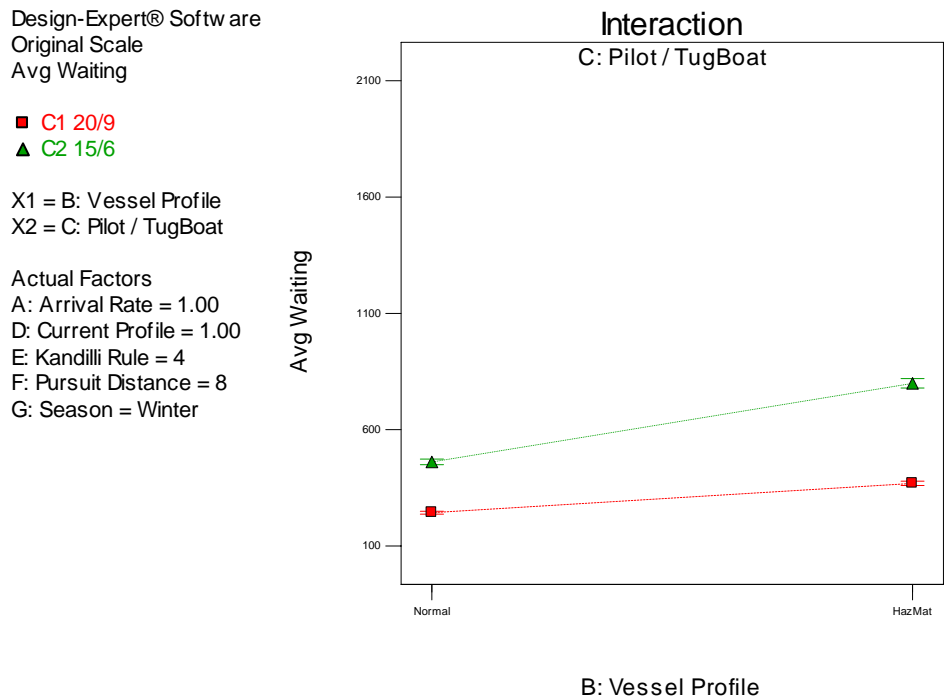


Figure C.25. Vessel profile – Pilot / Tugboat interaction effect on average waiting times

Design-Expert® Software
Original Scale
Avg Waiting

- G1 Summer
- ▲ G2 Winter

X1 = C: Pilot / TugBoat
X2 = G: Season

Actual Factors
A: Arrival Rate = 1.00
B: Vessel Profile = Normal
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8

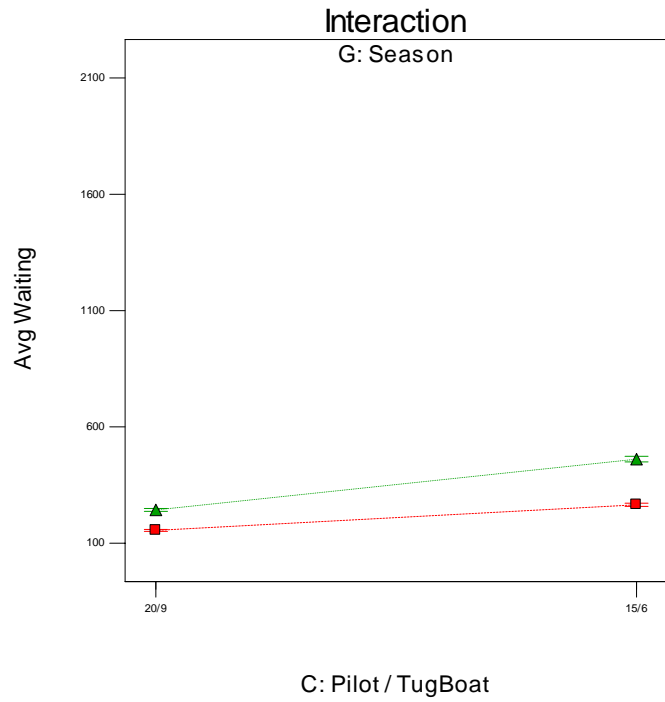


Figure C.26. Pilot / Tugboat – Season interaction effect on average waiting times

Table C.4. ANOVA table for maximum waiting times of vessels⁴

Source	Sum of Squares	df	Mean Square	F-Value	p-value (Prob > F)	
<i>Model</i>	665.70	12	55.47	771.79	< 0.0001	<i>significant</i>
<i>A-Arrival Rate</i>	264.59	1	264.59	3681.08	< 0.0001	
<i>B-Vessel Profile</i>	28.91	1	28.91	402.15	< 0.0001	
<i>C-Pilot / TugBoat</i>	203.27	1	203.27	2827.99	< 0.0001	
<i>D-Current Profile</i>	17.78	1	17.78	247.41	< 0.0001	
<i>F-Pursuit Distance</i>	3.50	1	3.50	48.71	< 0.0001	
<i>G-Season</i>	59.30	1	59.30	825.07	< 0.0001	
<i>AC</i>	51.85	1	51.85	721.35	< 0.0001	
<i>AD</i>	3.50	1	3.50	48.73	< 0.0001	
<i>AG</i>	0.59	1	0.59	8.22	0.0043	
<i>CG</i>	1.93	1	1.93	26.79	< 0.0001	
<i>DG</i>	3.41	1	3.41	47.39	< 0.0001	
<i>ACG</i>	27.07	1	27.07	376.60	< 0.0001	
<i>Residual</i>	45.07	627	0.07			
<i>Lack of Fit</i>	9.80	51	0.19	3.14	< 0.0001	<i>significant</i>
<i>Pure Error</i>	35.26	576	0.06			
<i>Cor Total</i>	710.77	639				
<i>Std. Dev.</i>	0.2681		<i>R-Squared</i>	0.9366		
<i>Mean</i>	9.87		<i>Adj R-Squared</i>	0.9354		
<i>C.V. %</i>	2.72		<i>Pred R-Squared</i>	0.9339		
<i>PRESS</i>	46.96		<i>Adeq Precision</i>	95.15		

Design-Expert® Software
Original Scale
Max Waiting

X1 = A: Arrival Rate

Actual Factors
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter

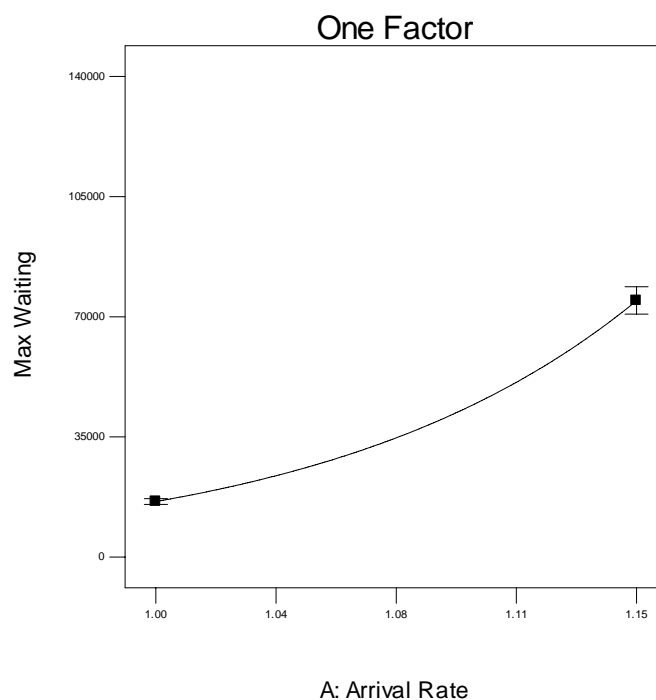


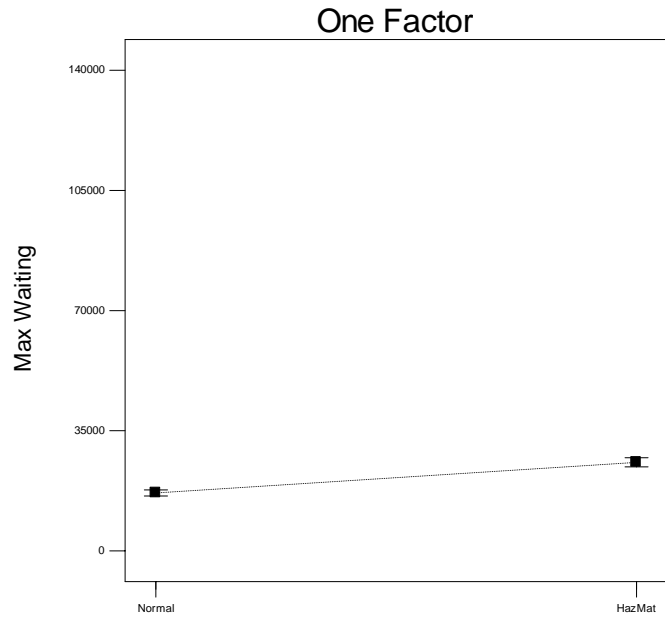
Figure C.27. Arrival rate effect on maximum waiting times

⁴ y' = $\ln y$ transformation is applied in the analysis of "Maximum waiting times of vessels" response

Design-Expert® Software
Original Scale
Max Waiting

X1 = B: Vessel Profile

Actual Factors
A: Arrival Rate = 1.00
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter



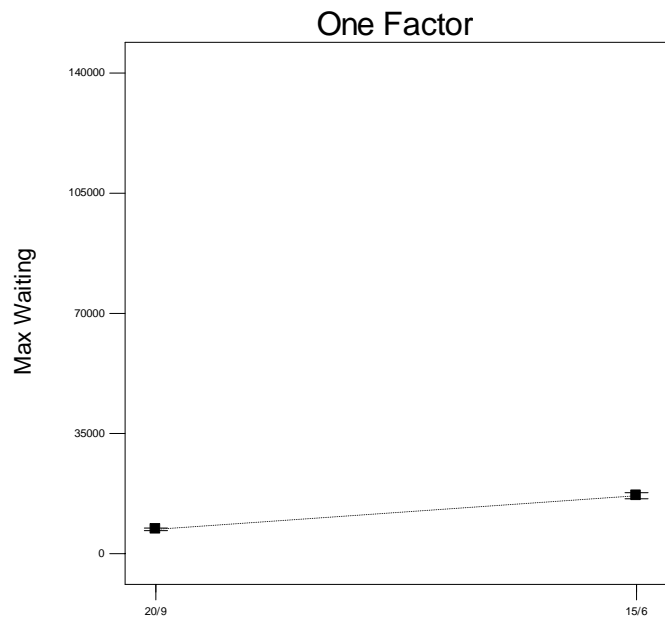
B: Vessel Profile

Figure C.28. Vessel profile effect on maximum waiting times

Design-Expert® Software
Original Scale
Max Waiting

X1 = C: Pilot / TugBoat

Actual Factors
A: Arrival Rate = 1.00
B: Vessel Profile = Normal
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter



C: Pilot / TugBoat

Figure C.29. Pilot / Tugboat effect on maximum waiting times

Design-Expert® Software
Original Scale
Max Waiting

X1 = D: Current Profile

Actual Factors
A: Arrival Rate = 1.00
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter

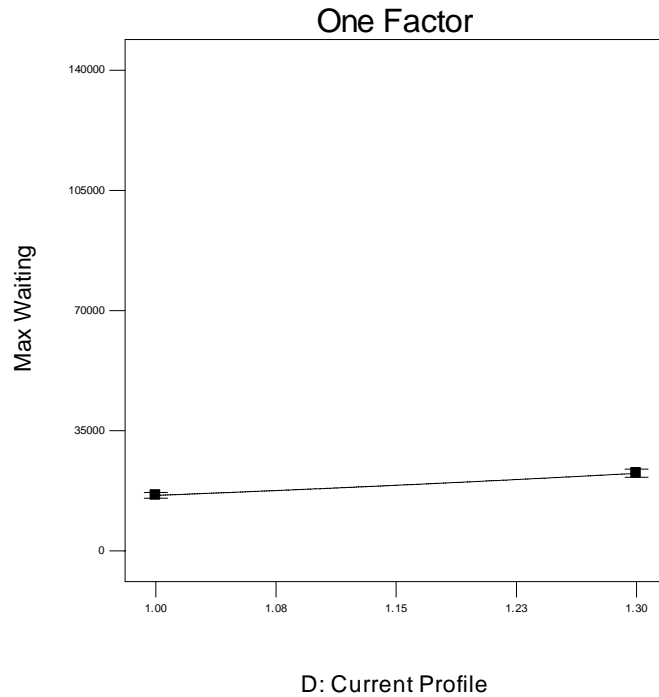


Figure C.30. Current profile effect on maximum waiting times

Design-Expert® Software
Original Scale
Max Waiting

X1 = F: Pursuit Distance

Actual Factors
A: Arrival Rate = 1.00
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
G: Season = Winter

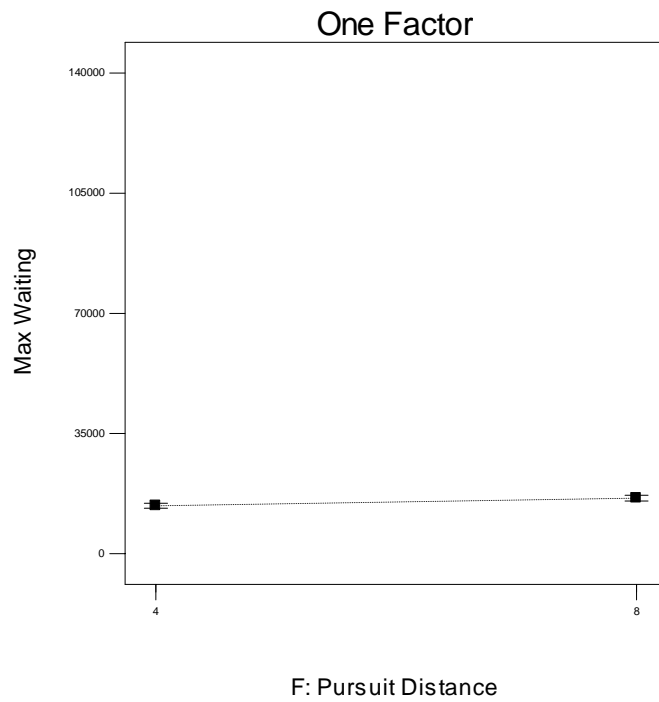


Figure C.31. Pursuit distance effect on maximum waiting times

Design-Expert® Software
Original Scale
Max Waiting

X1 = G: Season

Actual Factors
A: Arrival Rate = 1.00
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8

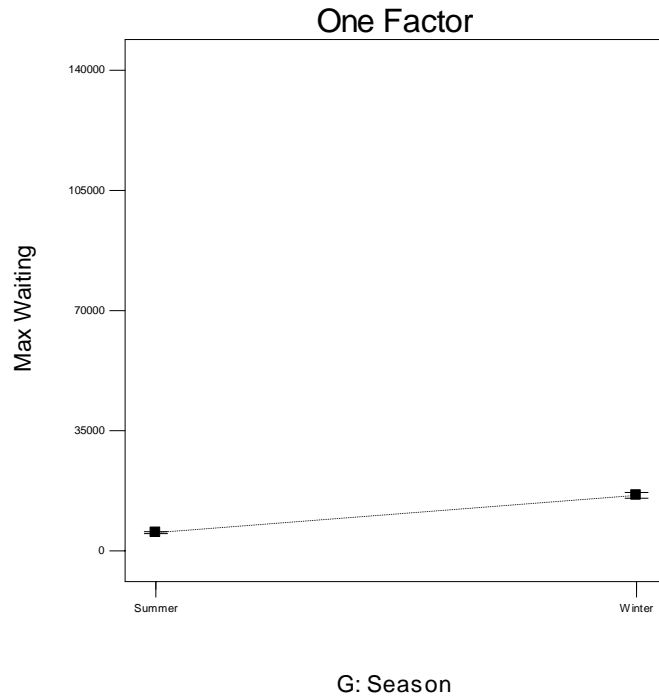


Figure C.32. Season effect on maximum waiting times

Design-Expert® Software
Original Scale
Max Waiting

■ C1 20/9
▲ C2 15/6

X1 = A: Arrival Rate
X2 = C: Pilot / TugBoat

Actual Factors
B: Vessel Profile = Normal
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter

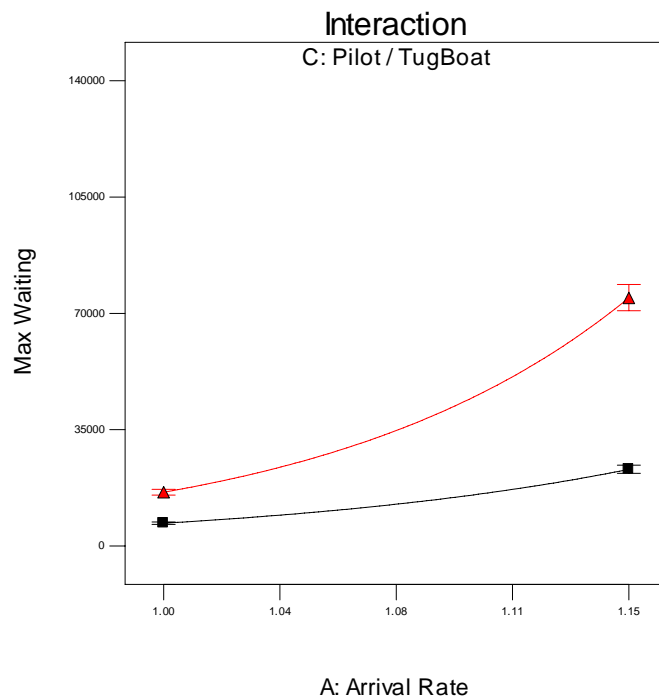


Figure C.33. Arrival rate - Pilot / Tugboat (when Season = winter) interaction effect on maximum waiting times

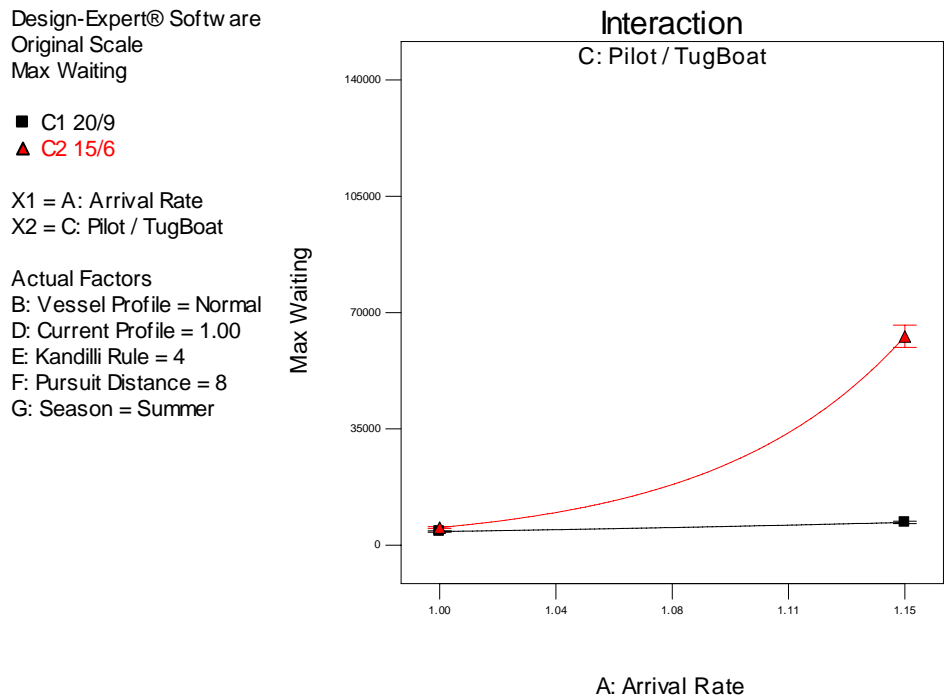


Figure C.34. Arrival rate - Pilot / Tugboat (when Season = summer) interaction effect on maximum waiting times

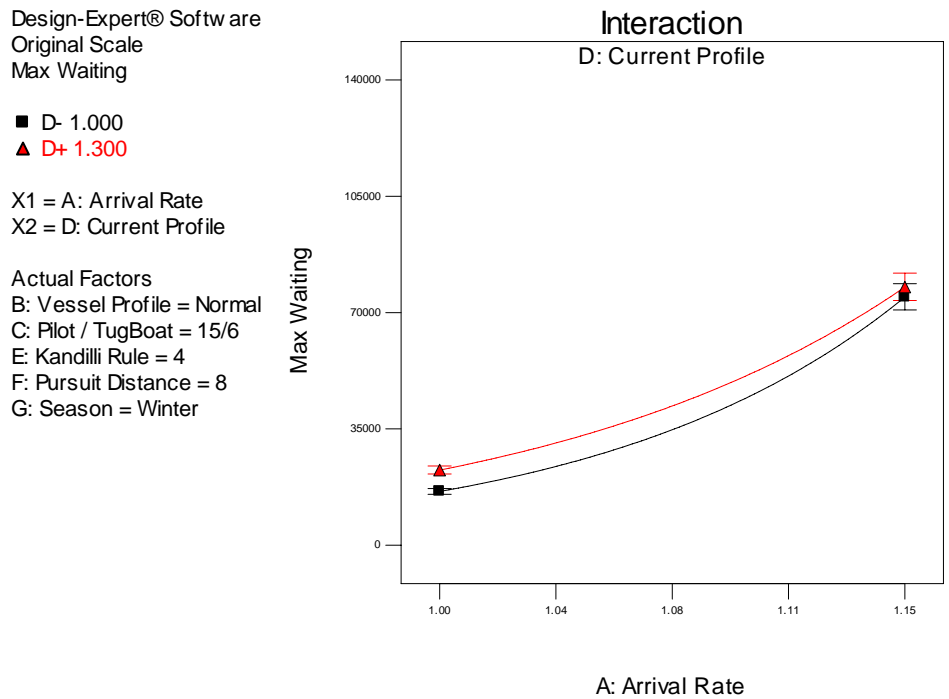


Figure C.35. Arrival rate – Current profile interaction effect on maximum waiting times

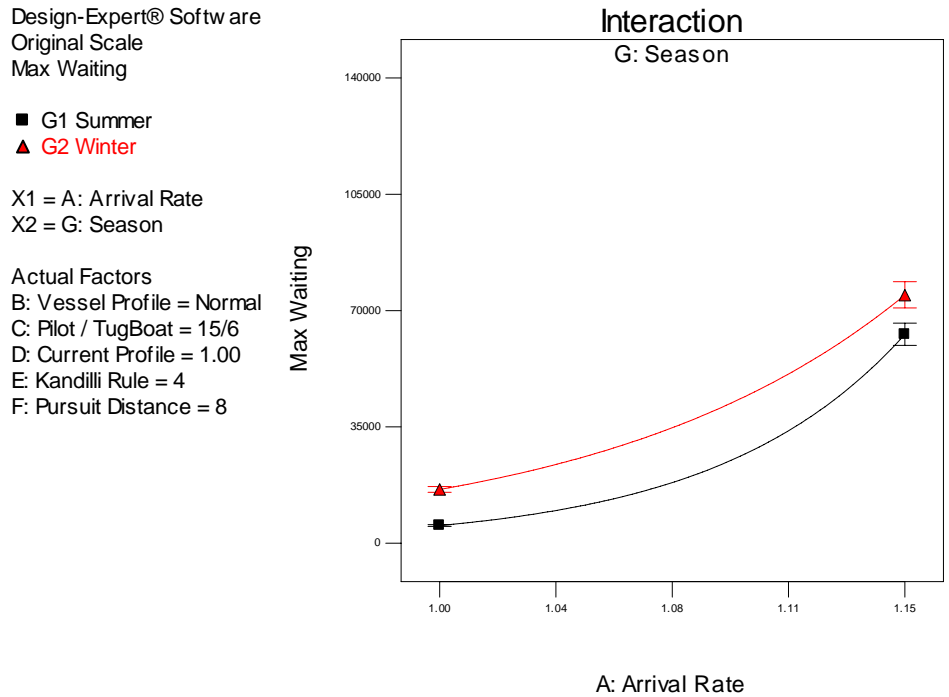


Figure C.36. Arrival rate – Season interaction effect on maximum waiting times

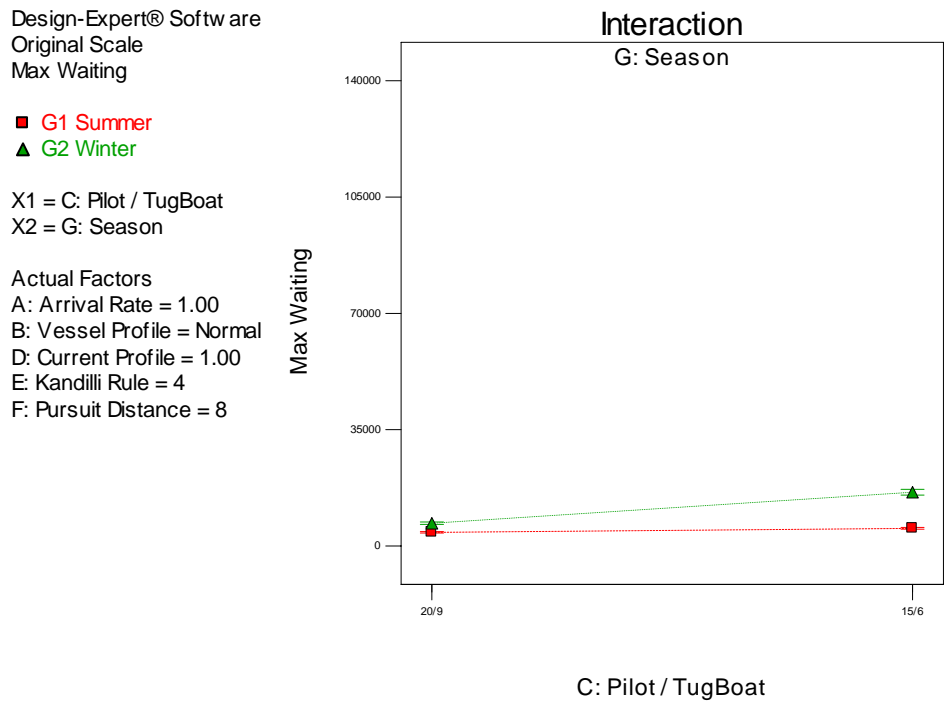


Figure C.37. Pilot / Tugboat – Season interaction effect on maximum waiting times

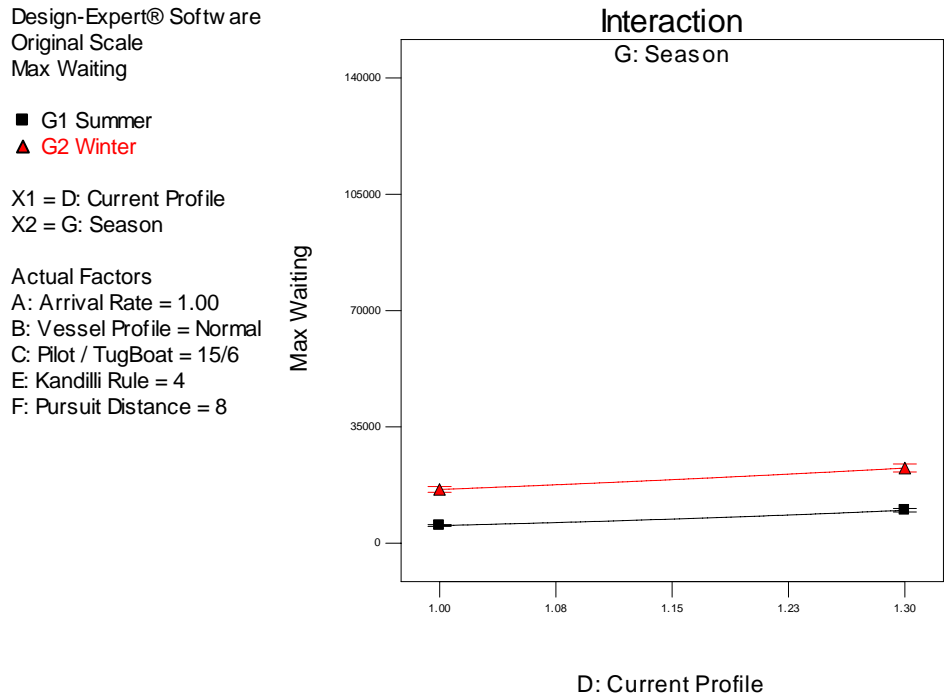


Figure C.38. Current profile – Season interaction effect on maximum waiting times

Table C.5. ANOVA table for number of vessels in queues⁵

Source	Sum of Squares	df	Mean Square	F-Value	p-value (Prob > F)	
<i>Model</i>	415.06	11	37.73	2602.59	< 0.0001	<i>significant</i>
<i>A-Arrival Rate</i>	204.41	1	204.41	14099.36	< 0.0001	
<i>B-Vessel Profile</i>	30.41	1	30.41	2097.53	< 0.0001	
<i>C-Pilot / TugBoat</i>	130.62	1	130.62	9009.27	< 0.0001	
<i>D-Current Profile</i>	1.22	1	1.22	84.44	< 0.0001	
<i>E-Kandilli Rule</i>	0.59	1	0.59	40.57	< 0.0001	
<i>F-Pursuit Distance</i>	11.36	1	11.36	783.30	< 0.0001	
<i>G-Season</i>	16.29	1	16.29	1123.59	< 0.0001	
<i>AC</i>	11.16	1	11.16	769.61	< 0.0001	
<i>AG</i>	0.15	1	0.15	10.34	0.0014	
<i>CG</i>	4.02	1	4.02	277.15	< 0.0001	
<i>ACG</i>	4.83	1	4.83	333.28	< 0.0001	
<i>Residual</i>	9.10	628	0.01			
<i>Lack of Fit</i>	1.71	52	0.03	2.55	< 0.0001	<i>significant</i>
<i>Pure Error</i>	7.40	576	0.01			
<i>Cor Total</i>	424.16	639				
<i>Std. Dev.</i>	0.1204		<i>R-Squared</i>	0.9785		
<i>Mean</i>	3.82		<i>Adj R-Squared</i>	0.9782		
<i>C.V. %</i>	3.15		<i>Pred R-Squared</i>	0.9777		
<i>PRESS</i>	9.46		<i>Adeq Precision</i>	180.07		

Design-Expert® Software
Original Scale
No in Queues

X1 = A: Arrival Rate

Actual Factors
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter

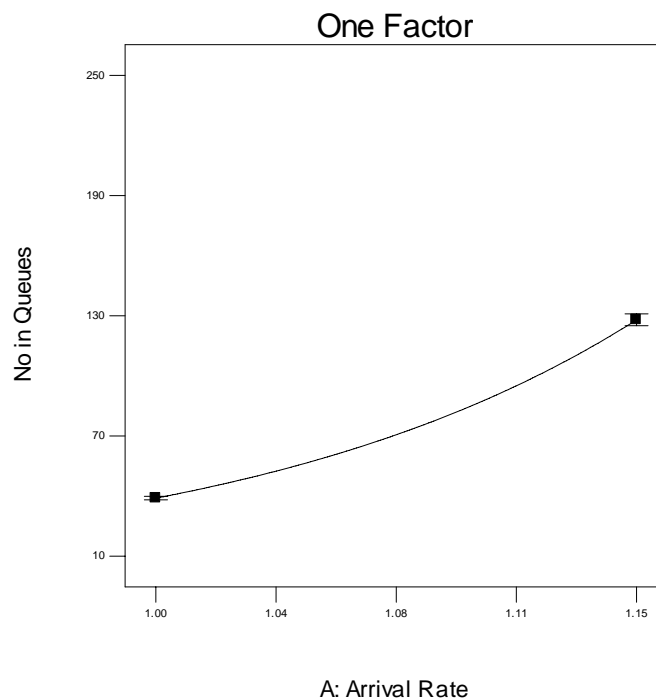


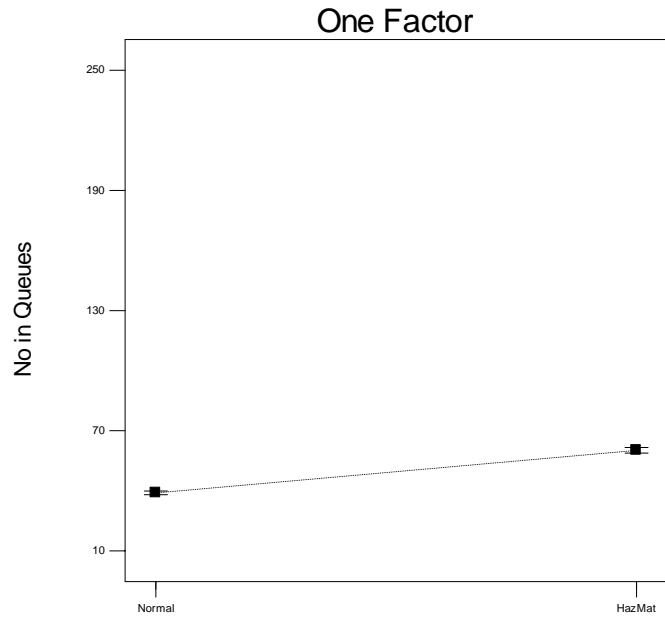
Figure C.39. Arrival rate effect on number of vessels in queues

⁵ y' = ln y transformation is applied in the analysis of "Number of vessels in queues" response

Design-Expert® Software
 Original Scale
 No in Queues

X1 = B: Vessel Profile

Actual Factors
 A: Arrival Rate = 1.00
 C: Pilot / TugBoat = 15/6
 D: Current Profile = 1.00
 E: Kandilli Rule = 4
 F: Pursuit Distance = 8
 G: Season = Winter



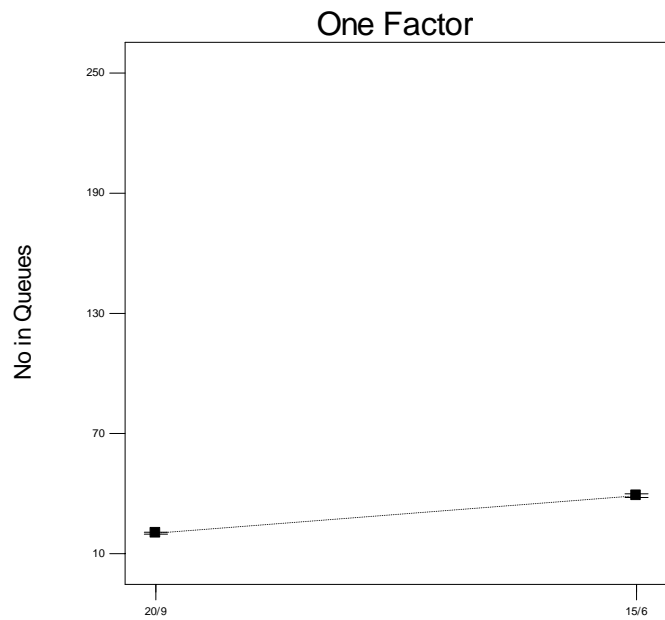
B: Vessel Profile

Figure C.40. Vessel profile effect on number of vessels in queues

Design-Expert® Software
 Original Scale
 No in Queues

X1 = C: Pilot / TugBoat

Actual Factors
 A: Arrival Rate = 1.00
 B: Vessel Profile = Normal
 D: Current Profile = 1.00
 E: Kandilli Rule = 4
 F: Pursuit Distance = 8
 G: Season = Winter



C: Pilot / TugBoat

Figure C.41. Pilot / Tugboat effect on number of vessels in queues

Design-Expert® Software
 Original Scale
 No in Queues

X1 = D: Current Profile

Actual Factors
 A: Arrival Rate = 1.00
 B: Vessel Profile = Normal
 C: Pilot / TugBoat = 15/6
 E: Kandilli Rule = 4
 F: Pursuit Distance = 8
 G: Season = Winter

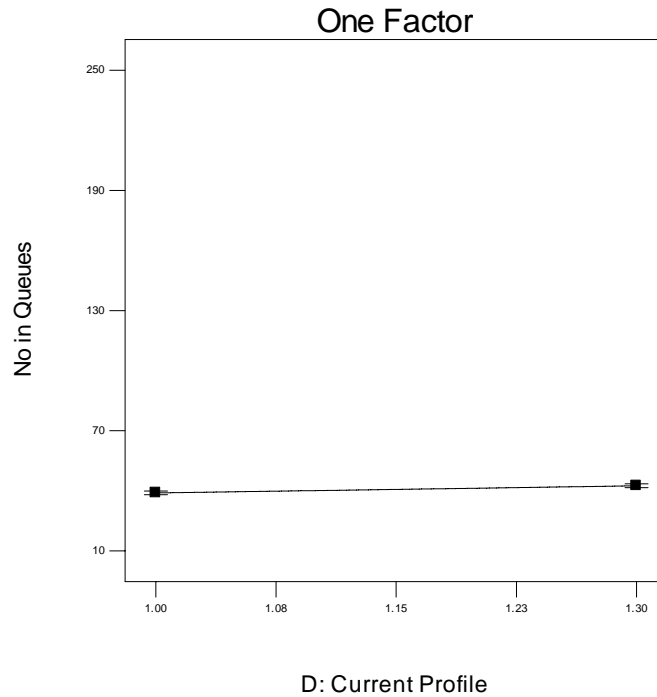


Figure C.42. Current profile effect on number of vessels in queues

Design-Expert® Software
 Original Scale
 No in Queues

X1 = E: Kandilli Rule

Actual Factors
 A: Arrival Rate = 1.00
 B: Vessel Profile = Normal
 C: Pilot / TugBoat = 15/6
 D: Current Profile = 1.00
 F: Pursuit Distance = 8
 G: Season = Winter

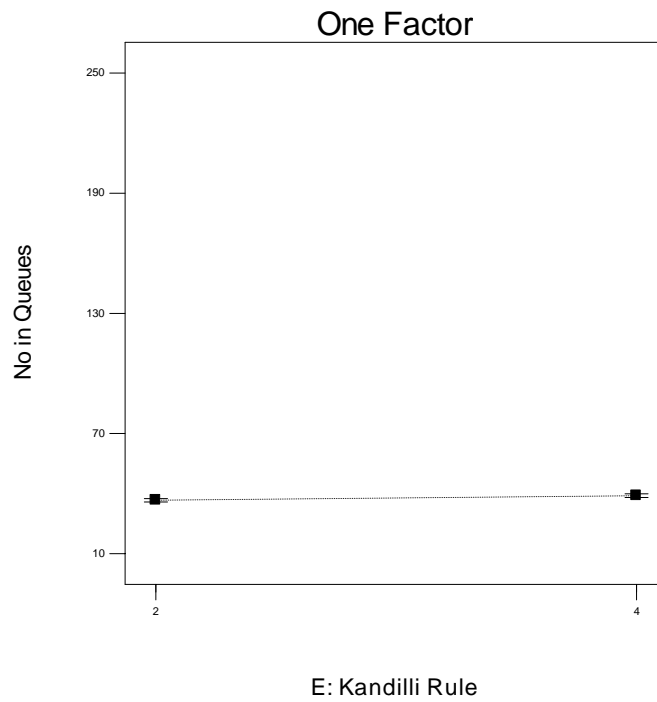


Figure C.43. Kandilli rule effect on number of vessels in queues

Design-Expert® Software
Original Scale
No in Queues

X1 = F: Pursuit Distance

Actual Factors
A: Arrival Rate = 1.00
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
G: Season = Winter

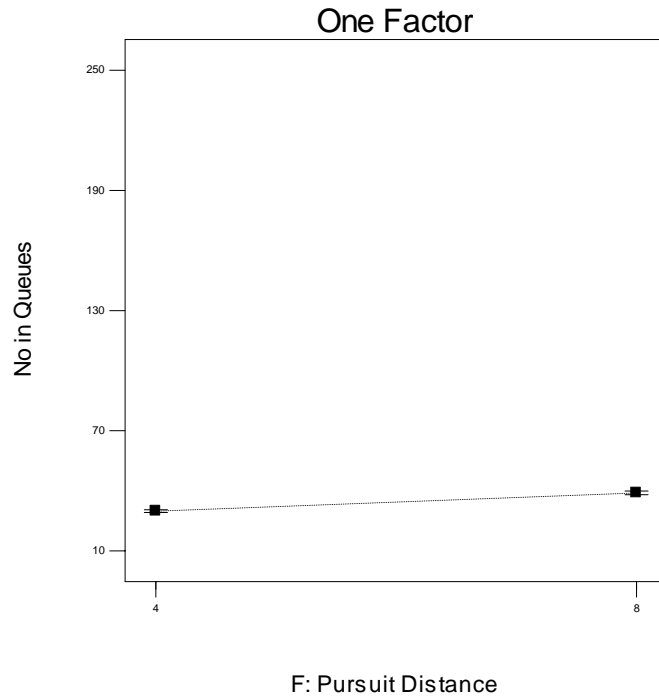


Figure C.44. Pursuit distance effect on number of vessels in queues

Design-Expert® Software
Original Scale
No in Queues

X1 = G: Season

Actual Factors
A: Arrival Rate = 1.00
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8

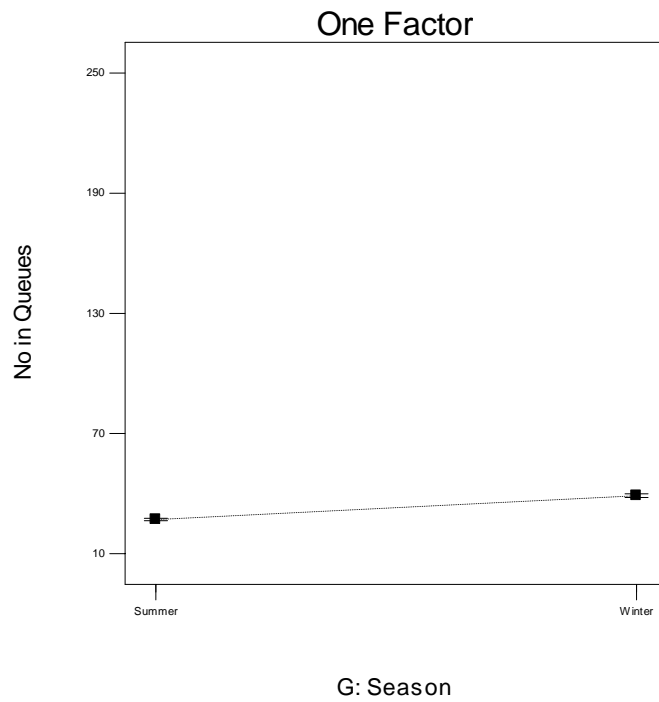


Figure C.45. Season effect on number of vessels in queues

Design-Expert® Software
Original Scale
No in Queues

- C1 20/9
- ▲ C2 15/6

X1 = A: Arrival Rate
X2 = C: Pilot / TugBoat

Actual Factors
B: Vessel Profile = Normal
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Winter

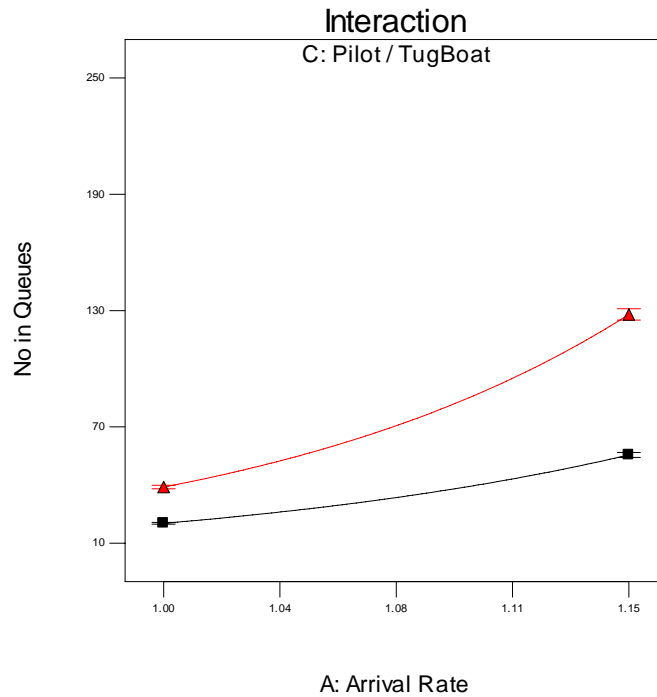


Figure C.46. Arrival rate - Pilot / Tugboat (when Season = winter) interaction effect on number of vessels in queues

Design-Expert® Software
Original Scale
No in Queues

- C1 20/9
- ▲ C2 15/6

X1 = A: Arrival Rate
X2 = C: Pilot / TugBoat

Actual Factors
B: Vessel Profile = Normal
D: Current Profile = 1.00
E: Kandilli Rule = 4
F: Pursuit Distance = 8
G: Season = Summer

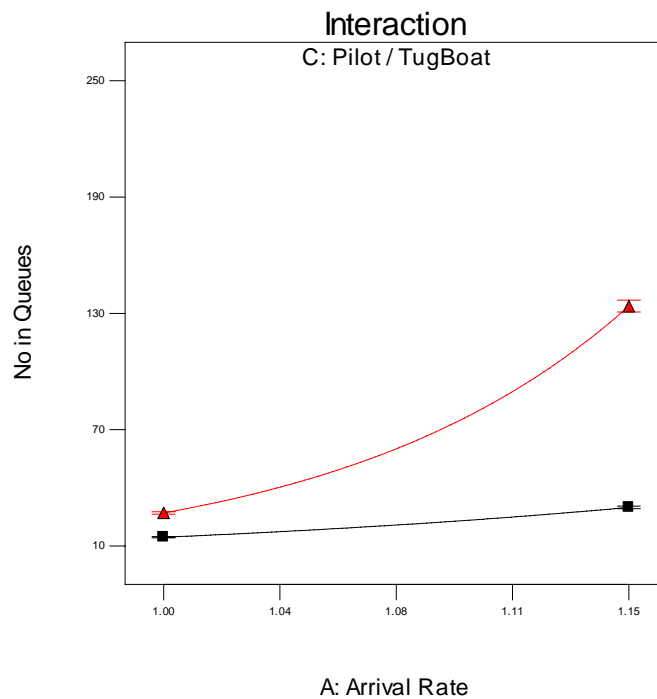


Figure C.47. Arrival rate - Pilot / Tugboat (when Season = summer) interaction effect on number of vessels in queues

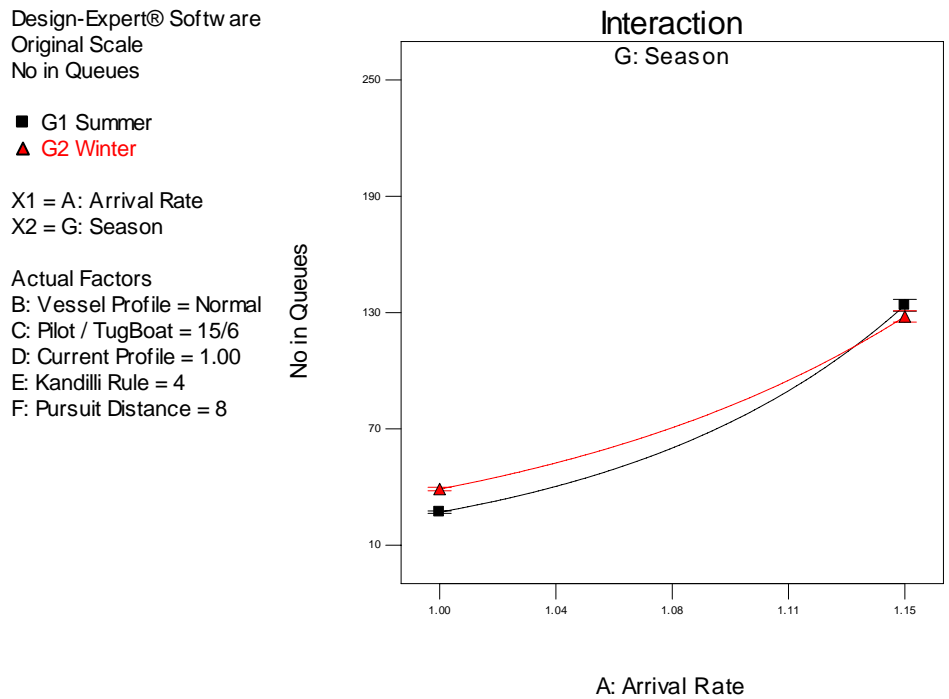


Figure C.48. Arrival rate - Season interaction effect on number of vessels in queues

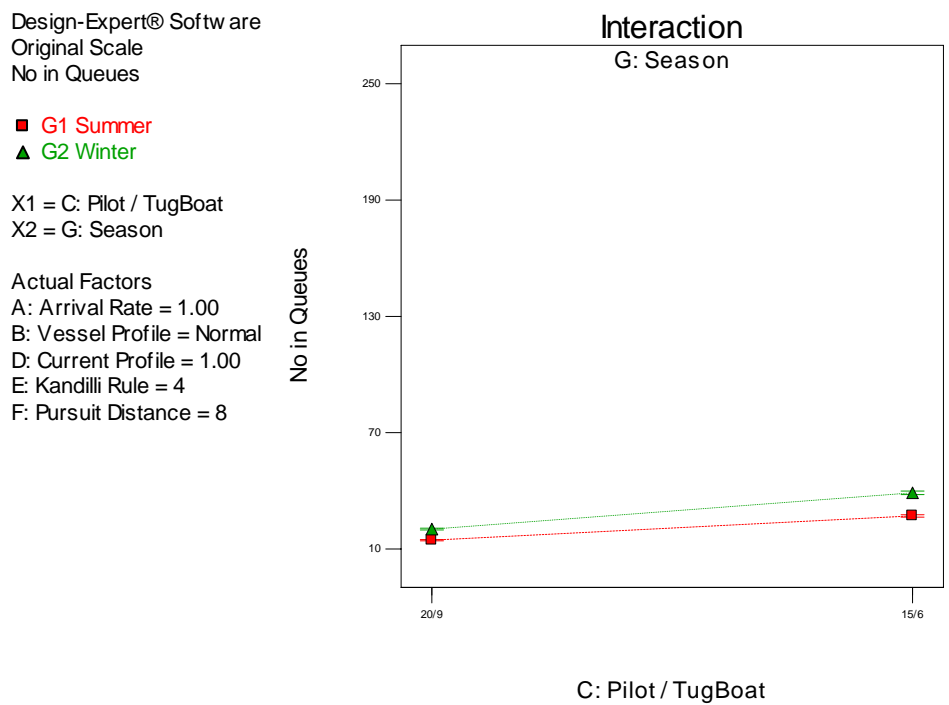


Figure C.49. Pilot / Tugboat - Season interaction effect on number of vessels in queues

Table C.6. ANOVA table for vessel density in the Strait

Source	Sum of Squares	df	Mean Square	F-Value	p-value (Prob > F)	
<i>Model</i>	2.3532	6	0.3922	8819.81	< 0.0001	<i>significant</i>
<i>A-Arrival Rate</i>	2.1832	1	2.1832	49095.99	< 0.0001	
<i>C-Pilot / TugBoat</i>	0.0093	1	0.0093	209.64	< 0.0001	
<i>D-Current Profile</i>	0.0167	1	0.0167	375.99	< 0.0001	
<i>F-Pursuit Distance</i>	0.1363	1	0.1363	3066.00	< 0.0001	
<i>AC</i>	0.0040	1	0.0040	90.92	< 0.0001	
<i>AF</i>	0.0036	1	0.0036	80.33	< 0.0001	
<i>Residual</i>	0.0281	633	0.00004			
<i>Lack of Fit</i>	0.0026	57	0.00005	1.03	0.4228	<i>not significant</i>
<i>Pure Error</i>	0.0255	576	0.00004			
<i>Cor Total</i>	2.3814	639				
<i>Std. Dev.</i>	0.0067		<i>R-Squared</i>	0.9882		
<i>Mean</i>	0.6876		<i>Adj R-Squared</i>	0.9881		
<i>C.V. %</i>	0.9698		<i>Pred R-Squared</i>	0.9879		
<i>PRESS</i>	0.0288		<i>Adeq Precision</i>	234.96		

Design-Expert® Software

Density in Channel

X1 = A: Arrival Rate

Actual Factors

B: Vessel Profile = Normal

C: Pilot / TugBoat = 15/6

D: Current Profile = 1.00

E: Kandilli Rule = 4

F: Pursuit Distance = 8

G: Season = Winter

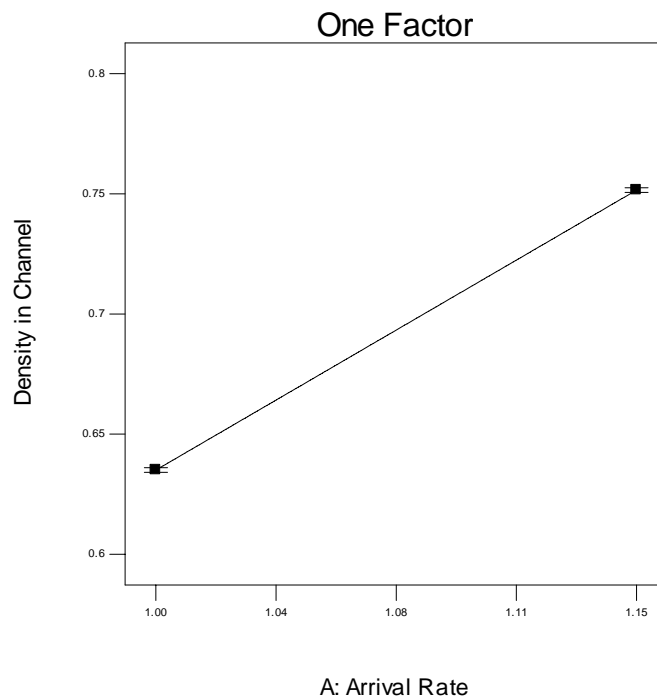


Figure C.50. Arrival rate effect on vessel density in the Strait

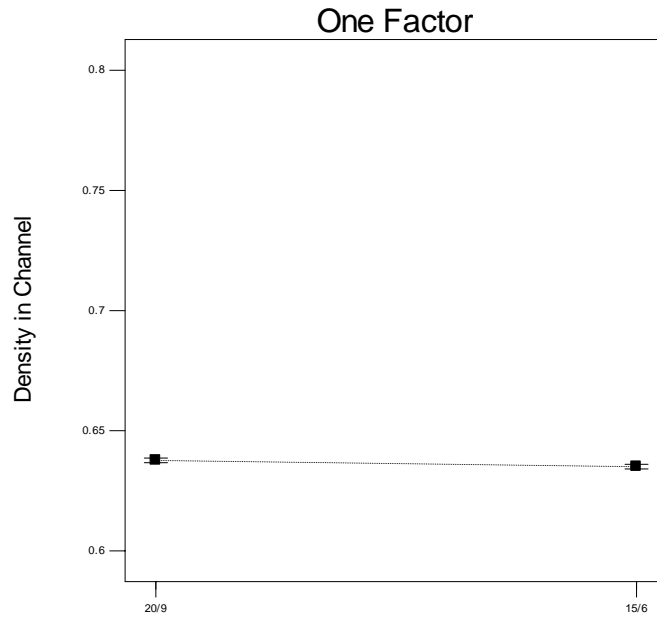
Design-Expert® Software

Density in Channel

X1 = C: Pilot / TugBoat

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8
- G: Season = Winter



C: Pilot / TugBoat

Figure C.51. Pilot / Tugboat effect on vessel density in the Strait

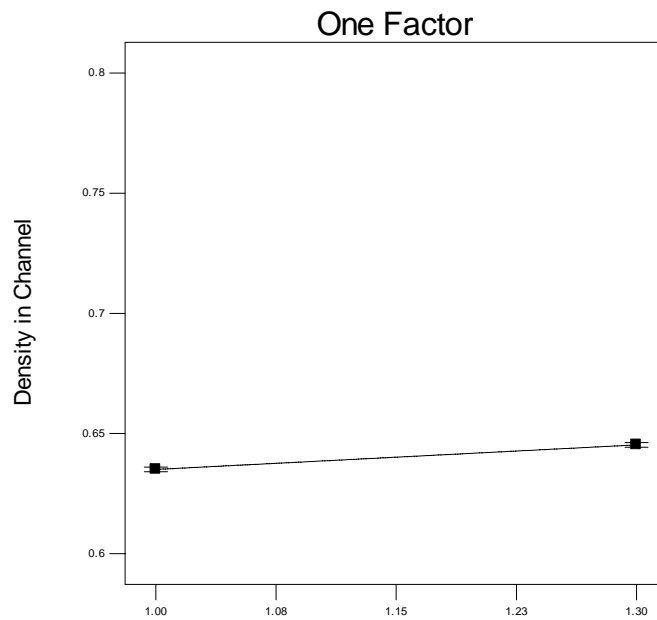
Design-Expert® Software

Density in Channel

X1 = D: Current Profile

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- C: Pilot / TugBoat = 15/6
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8
- G: Season = Winter



D: Current Profile

Figure C.52. Current profile effect on vessel density in the Strait

Design-Expert® Software

Density in Channel

X1 = F: Pursuit Distance

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- C: Pilot / TugBoat = 15/6
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- G: Season = Winter

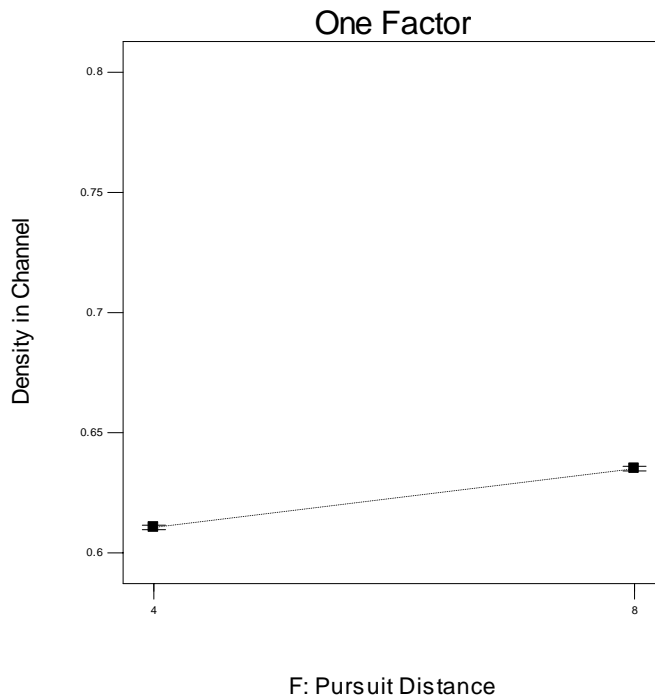


Figure C.53. Pursuit distance effect on vessel density in the Strait

Design-Expert® Software

Density in Channel

- C1 20/9
- ▲ C2 15/6

X1 = A: Arrival Rate
X2 = C: Pilot / TugBoat

Actual Factors

- B: Vessel Profile = Normal
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8
- G: Season = Winter

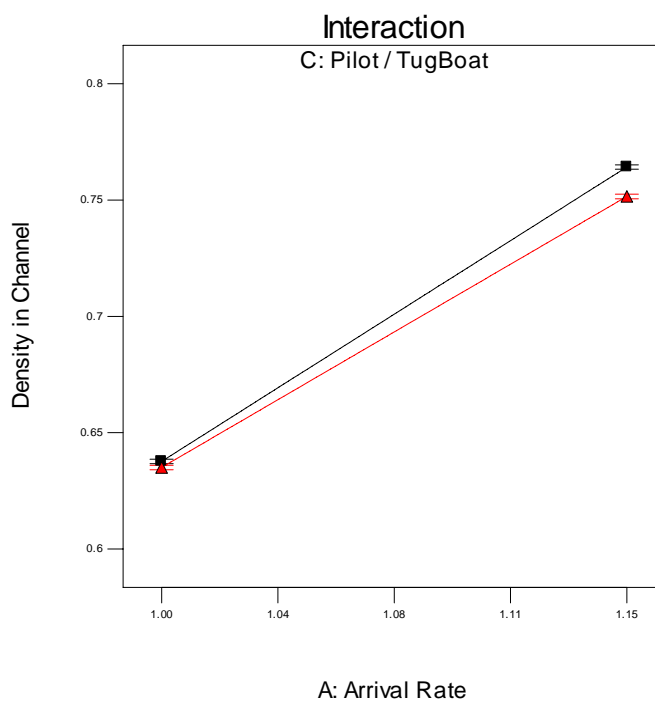


Figure C.54. Arrival rate –Pilot / Tugboat interaction effect on vessel density in the Strait

Design-Expert® Software

Density in Channel

■ F1 4

▲ F2 8

X1 = A: Arrival Rate

X2 = F: Pursuit Distance

Actual Factors

B: Vessel Profile = Normal

C: Pilot / TugBoat = 15/6

D: Current Profile = 1.00

E: Kandilli Rule = 4

G: Season = Winter

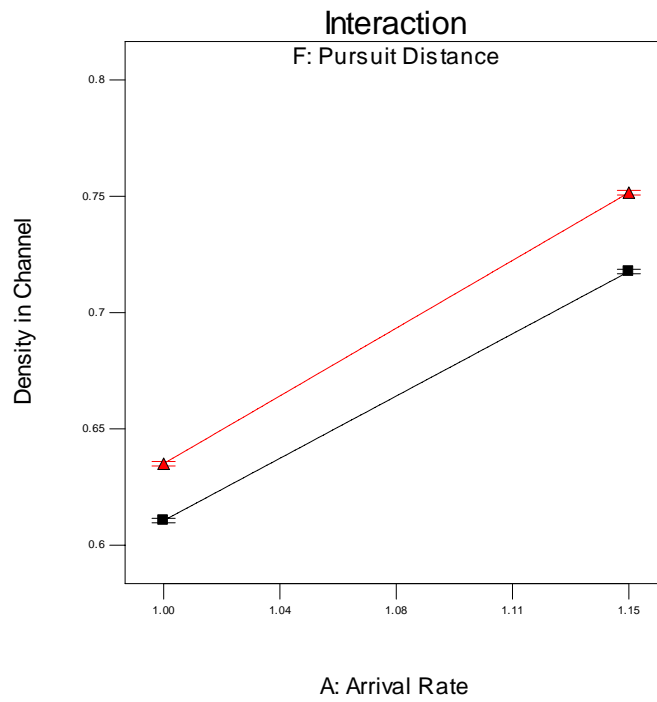


Figure C.55 Arrival rate –Pursuit distance interaction effect on vessel density in the Strait

Table C.7. ANOVA table for pilot utilization

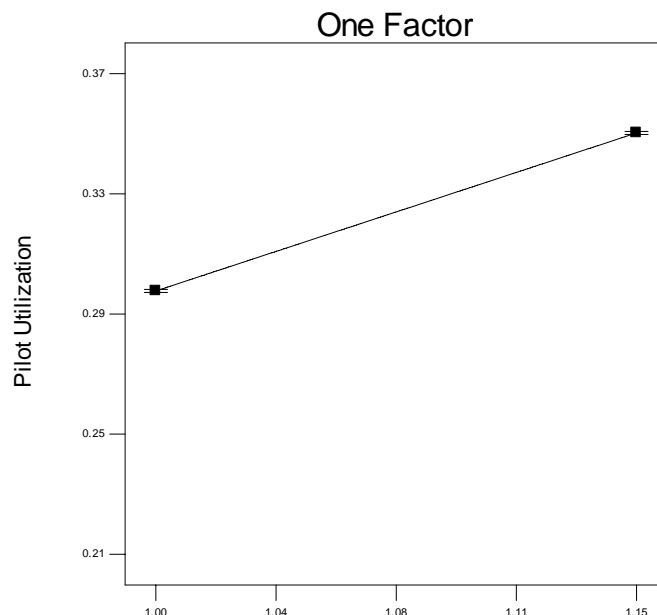
Source	Sum of Squares	df	Mean Square	F-Value	p-value (Prob > F)	
<i>Model</i>	1.3004	6	0.2167	16849.69	< 0.0001	<i>significant</i>
<i>A-Arrival Rate</i>	0.3481	1	0.3481	27058.54	< 0.0001	
<i>C-Pilot / TugBoat</i>	0.9212	1	0.9212	71617.35	< 0.0001	
<i>D-Current Profile</i>	0.0031	1	0.0031	239.08	< 0.0001	
<i>F-Pursuit Distance</i>	0.0250	1	0.0250	1940.18	< 0.0001	
<i>AC</i>	0.0024	1	0.0024	190.14	< 0.0001	
<i>AF</i>	0.0007	1	0.0007	52.87	< 0.0001	
<i>Residual</i>	0.0081	633	0.00001			
<i>Lack of Fit</i>	0.0010	57	0.00002	1.35	0.0513	<i>not significant</i>
<i>Pure Error</i>	0.0072	576	0.00001			
<i>Cor Total</i>	1.3086	639				
<i>Std. Dev.</i>	0.0036		<i>R-Squared</i>	0.9938		
<i>Mean</i>	0.2820		<i>Adj R-Squared</i>	0.9937		
<i>C.V. %</i>	1.27		<i>Pred R-Squared</i>	0.9936		
<i>PRESS</i>	0.0083		<i>Adeq Precision</i>	371.63		

Design-Expert® Software

Pilot Utilization

X1 = A: Arrival Rate

Actual Factors
 B: Vessel Profile = Normal
 C: Pilot / TugBoat = 15/6
 D: Current Profile = 1.00
 E: Kandilli Rule = 4
 F: Pursuit Distance = 8
 G: Season = Winter



A: Arrival Rate

Figure C.56 Arrival rate effect on pilot utilization

Design-Expert® Software

Pilot Utilization

X1 = C: Pilot / TugBoat

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8
- G: Season = Winter

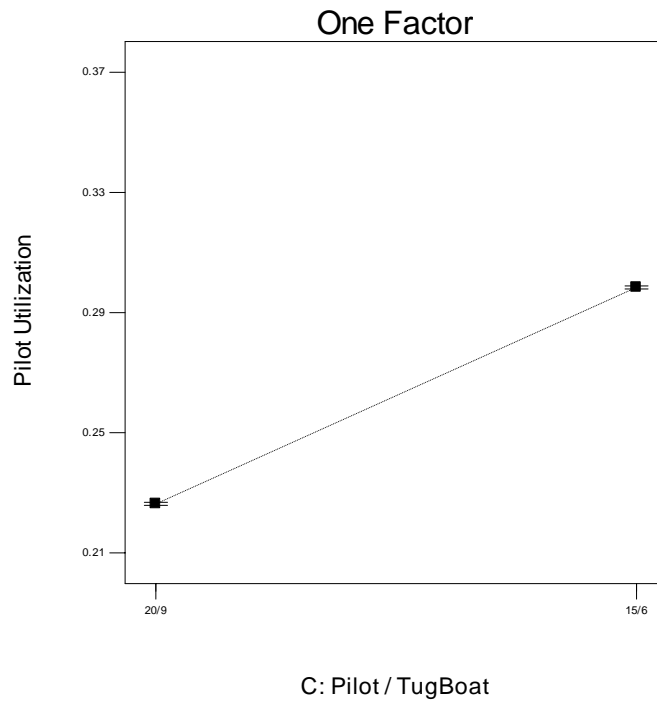


Figure C.57. Pilot / Tugboat effect on pilot utilization

Design-Expert® Software

Pilot Utilization

X1 = D: Current Profile

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- C: Pilot / TugBoat = 15/6
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8
- G: Season = Winter

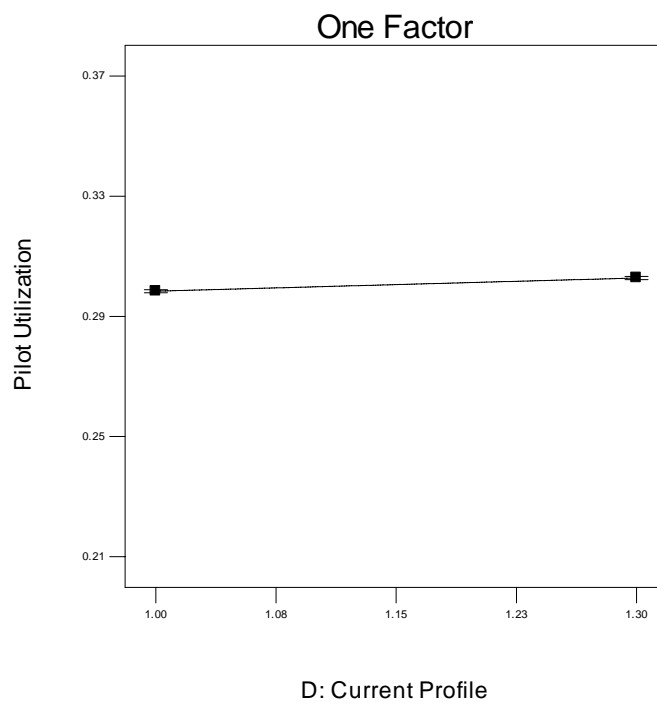


Figure C.58. Current profile effect on pilot utilization

Design-Expert® Software

Pilot Utilization

X1 = F: Pursuit Distance

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- C: Pilot / TugBoat = 15/6
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- G: Season = Winter

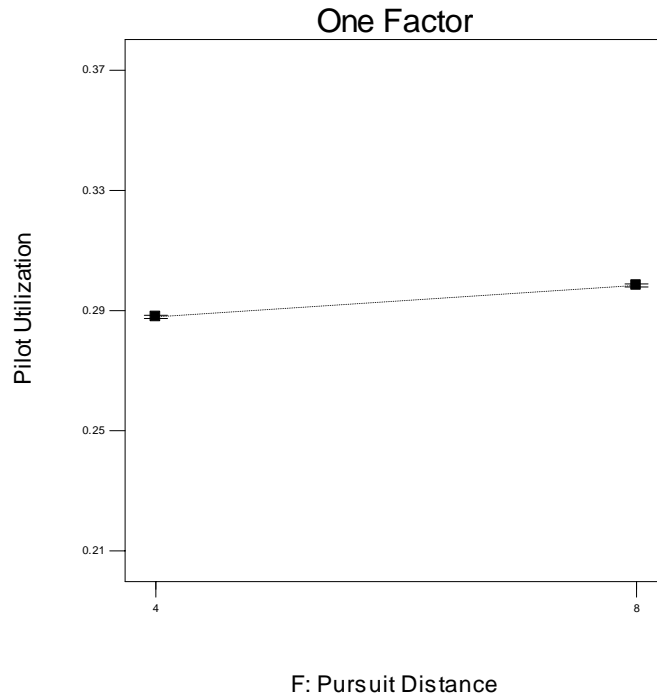


Figure C.59. Pursuit distance effect on pilot utilization

Design-Expert® Software

Pilot Utilization

- C1 20/9
- ▲ C2 15/6

X1 = A: Arrival Rate
X2 = C: Pilot / TugBoat

Actual Factors

- B: Vessel Profile = Normal
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8
- G: Season = Winter

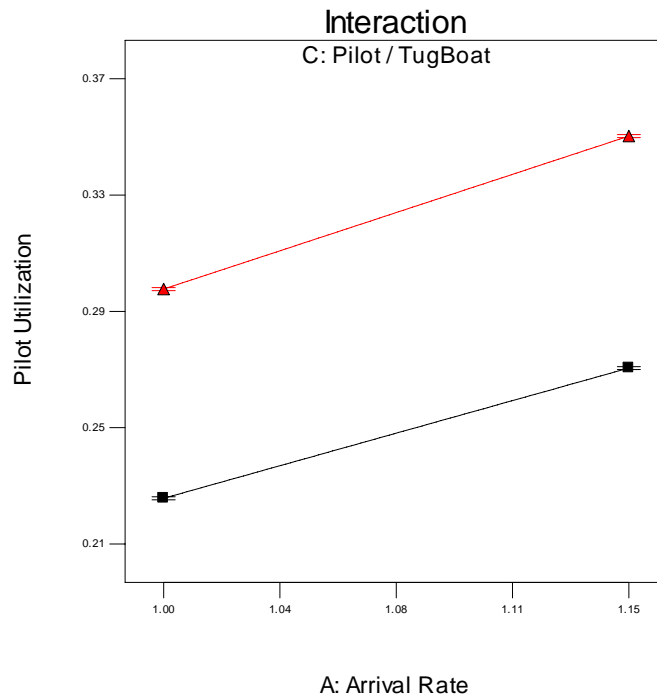


Figure C.60. Arrival rate – Pilot / Tugboat interaction effect on pilot utilization

Design-Expert® Software

Pilot Utilization

- F1 4
- ▲ F2 8

X1 = A: Arrival Rate
 X2 = F: Pursuit Distance

Actual Factors
 B: Vessel Profile = Normal
 C: Pilot / TugBoat = 15/6
 D: Current Profile = 1.00
 E: Kandilli Rule = 4
 G: Season = Winter

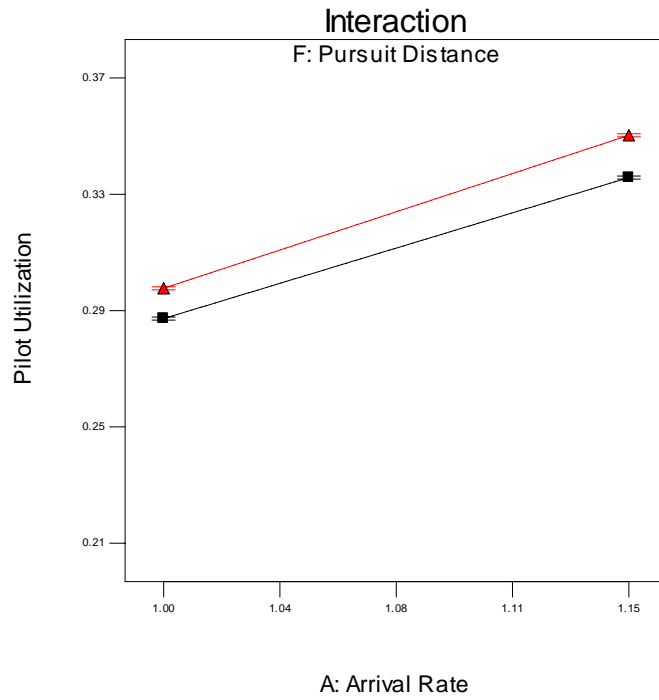


Figure C.61. Arrival rate – Pursuit distance interaction effect on pilot utilization

Table C.8. ANOVA table for tugboat utilization

Source	Sum of Squares	df	Mean Square	F-Value	p-value (Prob > F)	
Model	5.4658	6	0.9110	22980.81	< 0.0001	significant
A-Arrival Rate	0.8290	1	0.8290	20913.56	< 0.0001	
C-Pilot / TugBoat	4.5655	1	4.5655	115172.60	< 0.0001	
D-Current Profile	0.0096	1	0.0096	241.51	< 0.0001	
F-Pursuit Distance	0.0502	1	0.0502	1265.65	< 0.0001	
AC	0.0103	1	0.0103	260.45	< 0.0001	
AF	0.0012	1	0.0012	31.06	< 0.0001	
Residual	0.0251	633	0.00004			
Lack of Fit	0.0050	57	0.00009	2.49	< 0.0001	significant
Pure Error	0.0201	576	0.00003			
Cor Total	5.4909	639				
Std. Dev.	0.0063		R-Squared	0.9954		
Mean	0.4512		Adj R-Squared	0.9954		
C.V. %	1.40		Pred R-Squared	0.9953		
PRESS	0.0257		Adeq Precision	404.50		

Design-Expert® Software

Tugboat Utilization

X1 = A: Arrival Rate

Actual Factors

B: Vessel Profile = Normal

C: Pilot / TugBoat = 15/6

D: Current Profile = 1.00

E: Kandilli Rule = 4

F: Pursuit Distance = 8

G: Season = Winter

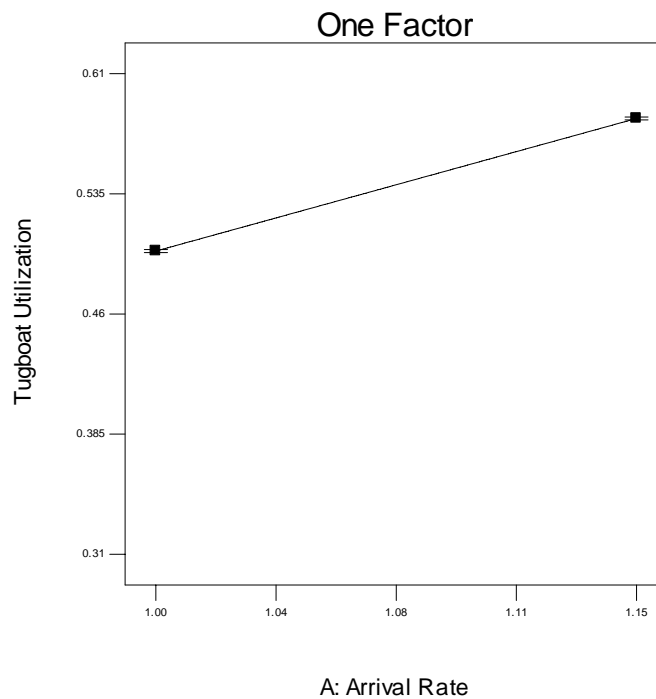


Figure C.62. Arrival rate effect on tugboat utilization

Design-Expert® Software

Tugboat Utilization

X1 = C: Pilot / TugBoat

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8
- G: Season = Winter

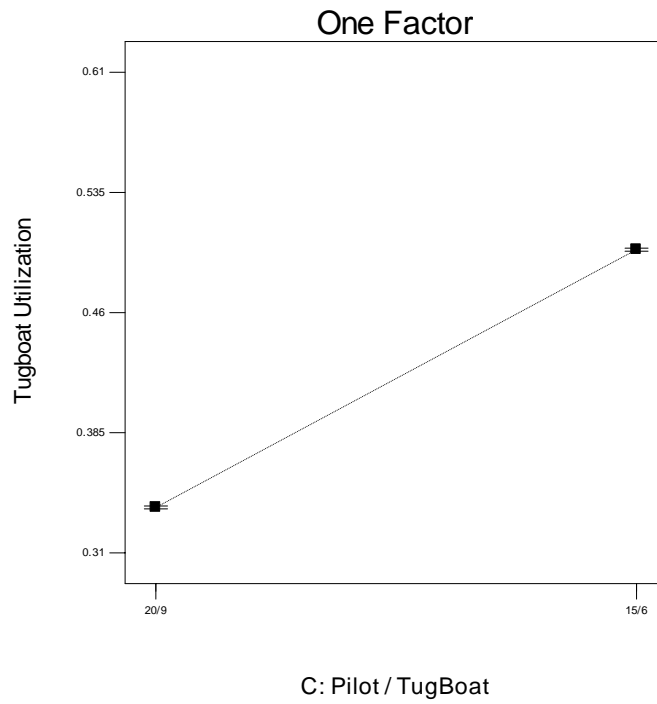


Figure C.63. Pilot / Tugboat effect on tugboat utilization

Design-Expert® Software

Tugboat Utilization

X1 = D: Current Profile

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- C: Pilot / TugBoat = 15/6
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8
- G: Season = Winter

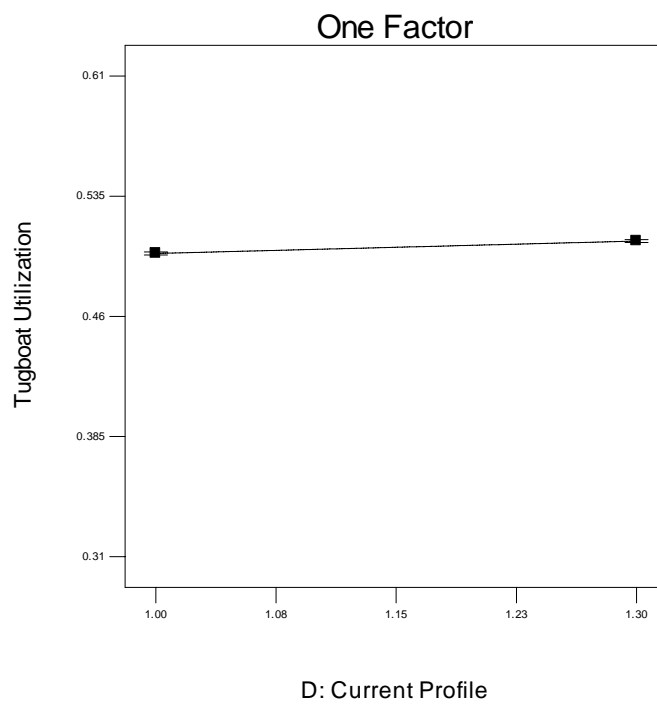


Figure C.64. Current profile effect on tugboat utilization

Design-Expert® Software

Tugboat Utilization

X1 = F: Pursuit Distance

Actual Factors

- A: Arrival Rate = 1.00
- B: Vessel Profile = Normal
- C: Pilot / TugBoat = 15/6
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- G: Season = Winter

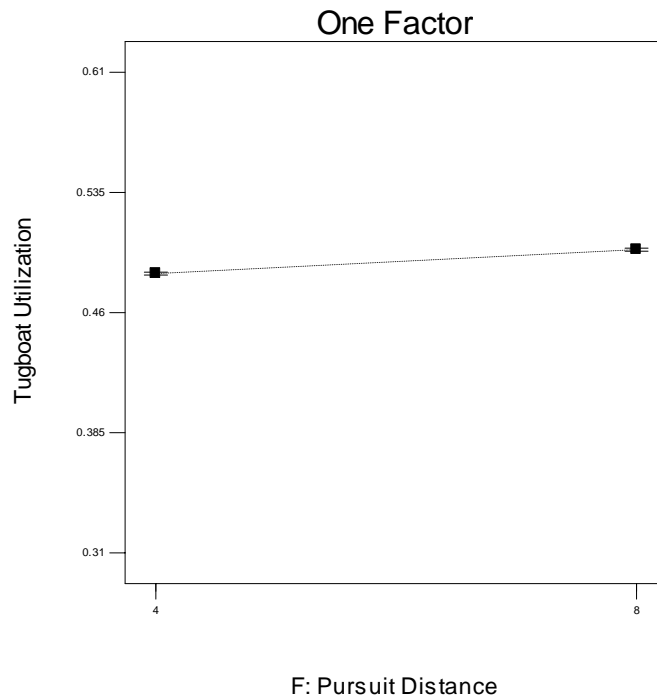


Figure C.65. Pursuit distance effect on tugboat utilization

Design-Expert® Software

Tugboat Utilization

- C1 20/9
- ▲ C2 15/6

X1 = A: Arrival Rate
X2 = C: Pilot / TugBoat

Actual Factors

- B: Vessel Profile = Normal
- D: Current Profile = 1.00
- E: Kandilli Rule = 4
- F: Pursuit Distance = 8
- G: Season = Winter

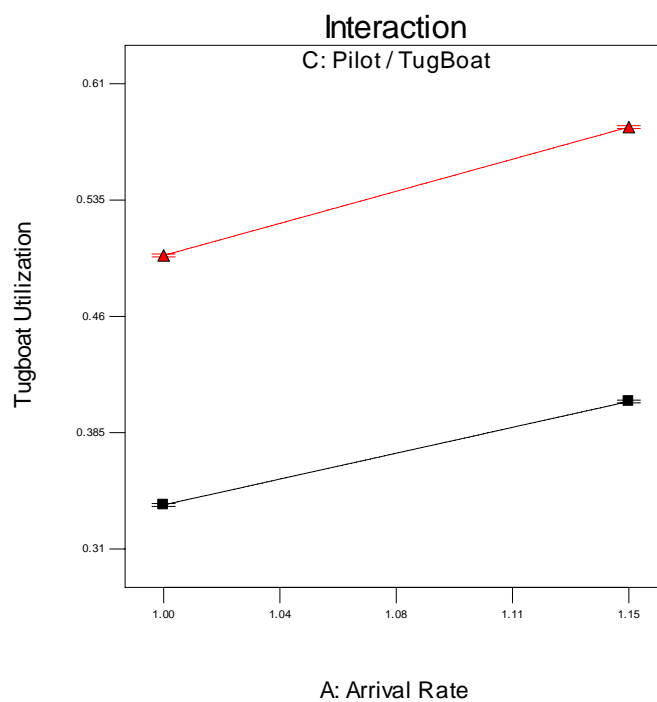


Figure C.66. Arrival rate – Pilot / Tugboat interaction effect on tugboat utilization

Design-Expert® Software

Tugboat Utilization

- F1 4
- ▲ F2 8

X1 = A: Arrival Rate
X2 = F: Pursuit Distance

Actual Factors
B: Vessel Profile = Normal
C: Pilot / TugBoat = 15/6
D: Current Profile = 1.00
E: Kandilli Rule = 4
G: Season = Winter

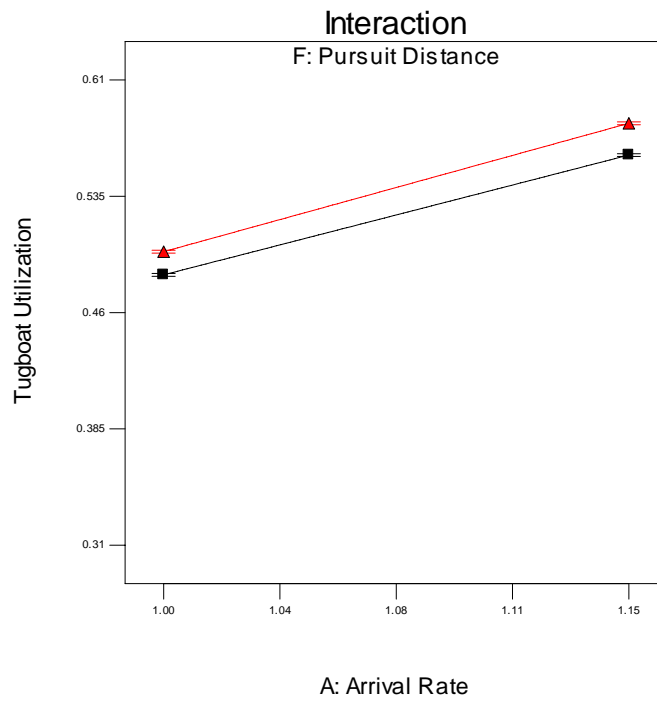


Figure C.67. Arrival rate – Pursuit distance interaction effect on tugboat utilization

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