# SIMULATION OF THE VESSEL TRAFFIC IN THE STRAIT OF ISTANBUL

by

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# ABSTRACT

## SIMULATION OF THE VESSEL TRAFFIC IN THE STRAIT OF ISTANBUL

Turkish Straits are of vital importance for Turkey since they interconnect the Mediterranean Sea and Black Sea. In particular the Istanbul Strait which is one of the narrowest and busiest waterways in the world (more than 50,000 vessels per year), carry high risks for both vessels and people living in Istanbul. In order to minimize these undesired incidents, the Turkish authorities establish maritime traffic regulations for vessels while entering and passing the Strait. In this study, a simulation model is designed to mimic the actual Istanbul Strait vessel flow under the established traffic regulations and meteorological conditions. Arriving vessels which are classified according to their cargo and length usually have to wait a certain amount of time (in their respective queues according to type and length) before being admitted to the Strait (due to the main traffic regulations regarding vessel density and composite sailing in the Strait). The one way daytime traffic starting direction and number of vessels planned to enter from each direction are formulized and vessels with respect to their assigned priorities transit in this direction when the determined minimum pursuit distances between each other, meteorological conditions and tugboat or pilot needs are satisfied. The number and types of vessels scheduled in nighttime traffic (which allows two way transits) is also formulized. The number of pilots and tugboats scheduled in the traffic flow direction, visibility, current and storm information are also integrated to the model. In this respect, average waiting time of vessels and for each class, total number of vessels passed from each direction, transit times, number of vessels in the queues, vessel densities throughout the Strait and pilot utilizations are selected as performance measures and their results are compared with the actual values obtained from 2009 data for investigating the model accuracy. Furthermore, the individually and interactive effects of vessel arrival rate, number of available pilots in the system, vessel profiles and minimum pursuit distances on the performance measures are investigated is concluded that arrival rate is the most influencing

factor among others. Finally, the effect of visibility when the arrival rate is also at high rates is also analyzed and is deduced that the fog density in the Strait is also significant for the system performance measures.

# ÖZET


## İSTANBUL BOĞAZI GEMİ TRAFİĞİNİN SİMÜLASYONU

Türk Boğazları Akdeniz ve Karadeniz'i birbirine bağlamaları sebebiyle Türkiye için büyük önem arz etmektedirler. Özellikle, dünyanın en dar ve yılda 50000'i aşkın gemi geçişiyle en yoğun su yollarından biri olan İstanbul Boğazı gemiler ve İstanbul'da yaşayan insanlar için büyük riskler taşımaktadır. Bu istenmeyen olayları en aza indirmek için Türk yetkililer İstanbul Boğazı'na giriş ve Boğaz'dan geçişte deniz trafiği düzenlemelerini yürürlüğe koymaktadırlar. Bu çalışmada söz konusu düzenlemeler ve meteorolojik şartlar altında mevcut İstanbul Boğazı gemi trafik akışını benzetmek için bir simülasyon modeli kurulmuştur. Taşıdıkları yüklere ve uzunluklarına gore sınıflandırılırlarak Boğaz'a gelen gemiler genellikle bir süre yük ve uzunluklarına göre belirlenen kuyruklarında Boğaz'a alınmak için beklerler (gemi yoğunluğu ve bileşik seyiri dikkate alan temel trafik düzenlemeleri sebebiyle). Tek yönlü gündüz trafik yönü ve her yönden kaç gemi geçeceği formulize edilmiştir ve gemiler belirlenen en küçük takip mesafesi şartı sağlandığında, meteorolojik şartlar elverdiğinde ve pilot ve römorkör ihtiyaçları karşılandığı taktirde kendilerine atanan öncelik derecelerine göre bu yönden geçiş yaparlar. Çift yönlü geçişe izin veren gece trafiğinde geçecek riskli gemilerin sayısı ve tipleri de formulize edilmiştir. Trafik akış yönünde çizelgelenen pilot ve römorkör sayısı, görüş uzaklığı kapasitesi, akıntı ve fırtına bilgileri de modele eklenmiştir. Bu bağlamda, gemilerin ve her gemi sınıfının ortalama bekleme zamanı, her yönden geçen toplam gemi sayısı, kuyruktaki gemi sayısı, Boğazdaki gemi yoğunluğu ve pilot kullanımı başarı ölçütleri olarak seçilmiş ve sonuçları modelin doğruluğunu araştırmak için 2009'daki gerçek değerlerle karşılaştırılmıştır. Ayrıca, gemi geliş oranı, sistemdeki mevcut pilot sayısı, gemi profili ve en küçük takip mesafesinin ayrı ayrı ve etkileşimli olarak başarı ölçütleri üzerinde etkileri araştırılmış ve gemi geliş oranının en büyük öneme sahip olduğu sonucuna varılmıştır. Son olarak, gemi geliş oranı yüksek iken görüş uzaklığı kapsitesi incelenmiş ve Boğaz'daki sis yoğunluğunun da sistem performans ölçütleri üzerinde etkili olduğu çıkarımında bulunulmuştur.

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| | |
|---|---|
| ANOVA | Analysis of variance |
| FogType1 | Type of fog closing one way traffic in the Istanbul Strait |
| FogType2 | Type of fog closing all traffic in the Istanbul Strait |
| HazMat | Hazardous material |
| LNG | Liquefied natural gas |
| LPG | Liquid petroleum gas |
| NB | Northbound transiting vessel |
| Prob > F | The upper bound of the P-value |
| R&R | Istanbul Strait Traffic Rules and Regulations |
| SB | Southbound transiting vessel |
| SP-1 | Sailing Plan 1 |
| SP-2 | Sailing Plan 2 |
| SS | Sum of squares |
| TSVTS | Turkish Straits Vessel Traffic Service Center |
| VTS | Vessel Traffic System |

# 1. INTRODUCTION AND STUDY OBJECTIVES

What sets Turkish Straits apart from other channels is that they connect the Black Sea and the Mediterranean Sea while separating Asia and Europe continents. Both having geopolitical importance for Turkey, The Strait of Istanbul which is situated in the middle of a huge metropolitan area of 15 million residents has many exceptional properties, while carrying both high advantages and risks for the vessels navigating through it. It also carries a very heavy maritime traffic. Although transit maritime traffic was about 30,000 vessels annually in the 1990's, currently more than 55,000 vessels pass through the Strait; with more than 15,000 such vessels carrying dangerous cargo. In addition to the international maritime traffic, there is also heavy local traffic including more than 2000 passenger ferry trips daily between the two shores [4]. Possible accidents involving these vessels may have disastrous effects for the city of Istanbul and its population and for the economies of the Black Sea countries, Caucasian and Central Asian States [1].

The Istanbul Strait is 31 kilometers length and 1,5 km width. It is the narrowest waterway in the world with only 660 meters at its narrowest point between Rumelihisarı and Anadolu Hisarı (Figure 1.1). The deepest point is at Kandilli and Bebek with 120 meters [2]. Vessels navigating through the Strait have to make many sharp turns (between 45 and even 80 degrees) which carries high risks for the vessels in such a narrow channel [3].

One other noteworthy and treacherous property of the Strait of Istanbul is the prevailing currents which may rise up to 6 or 8 knots speed [1]. The Strait is exposed to surface currents, reverse currents, undertow currents and orkoz currents, the most dominant one is the southbound surface current caused by level difference between the Black Sea and the Mediterranean Sea [2].

Adverse meteorological conditions like fog, wind, rain and storm also increase the difficulty of navigation on the Strait. In dense fog conditions, vessel traffic may be partially or wholly suspended until meteorological conditions improve which causes dangerous and unwanted pile-ups at the Strait entrances and puts further strains on the maritime traffic management since it increases navigation problems [1]. Storms also hinder the Strait traffic since they may restrain small vessels from moving on to the open seas beyond the Strait. Vessel type and cargo, pilot and tugboat availabilities become more critical in adverse natural conditions cases [4].

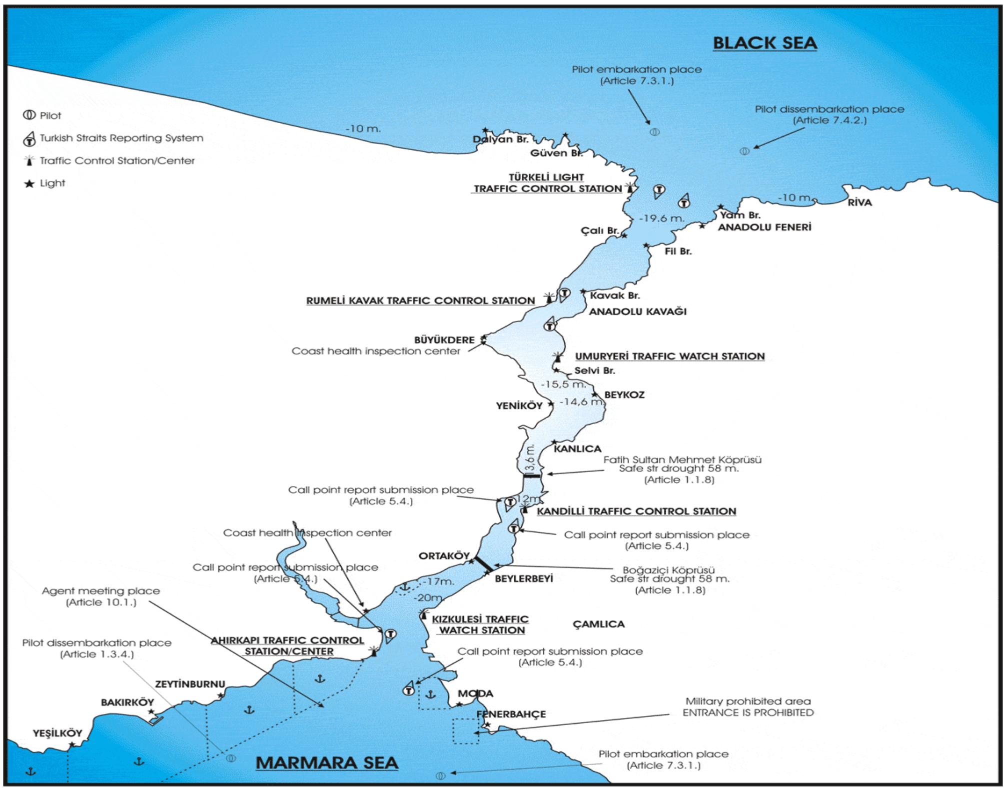


Figure 1.1. The Istanbul Strait

As mentioned, the Istanbul Strait carries not only passenger and dry cargo vessels but also tankers and other hazardous material vessels which may generate additional risks.

Vessels are allowed into the Turkish Straits based on well defined and strict laws and regulations. The Turkish Straits Vessel Traffic Service (TSVTS) is established in 2004 in order to regulate and guide maritime traffic on the Istanbul and Çanakkale Straits, in accordance with international and national conventions and regulations, while improving safe navigation, protecting life and environment. The Vessel Traffic System (VTS) is technically supported by a high technology integrated radar, cameras, sensors and communication system in carrying out its responsibilities [5]. Within the framework of this system, vessels desiring to transit the Strait have to submit two reports, Sailing Plan 1 (SP-1) and Sailing Plan 2 (SP-2). SP-1 includes all the information about the vessel and must be submitted at least 24 hours before the arrival. SP-2 is of vital importance for the planning of vessel passages from the Strait and must be submitted at least 2 hours or 20 nautical miles (whichever comes first) prior to entry into the Strait [1]. The VTS analyze the data in their reports and prepare a safe daily sailing traffic plan.

Tugboat and pilot services are critically important especially in extreme, environmental conditions and in human or equipment failures. Turkish maritime pilots are fully aware of the Strait traffic risks and potential strong tidal flows, while the master of the vessel may not be fully familiar with the area and the likely navigational problems on the Strait. Pilots can easily and instantly communicate with the VTS about the current situation at any moment. Tugboat escorts on the other hand, are strongly recommended for all vessels in adverse meteorological and equipment conditions. Therefore, the VTS provide pilot and tugboat services to reduce the maritime risks.

## 1.1. Accidents in Istanbul Strait

Unfortunately the Istanbul Strait has witnessed many maritime accidents (some with dire consequences) over the years. It is worthwhile to mention some of these accidents. In 1960, the Greek-flagged World Harmony and the Yugoslavian-flagged Zoranic had a collision causing the death of 20 crew members and polluting the sea. In 1966, two Russia-flagged vessels, Kransky and Lutsk, collided in the Strait causing a major oil spill whose fierce burning necessitated the closure of the Strait for days. The Karaköy Pier and a local ferry boat were also incinerated in that fire. In 1979, the Romanian-flagged tanker Independeta (carrying 100,000 tons of crude oil) and Greek-flagged Evriyali collided, causing the death of 43 crew members and spilling hundreds tons of oil to the sea. The resulting fire and Strait closure lasted for days. In 1991, Lebanon–flagged Rabinion and Philippines-flagged dry cargo ship Madonna Lily collided, 21,000 sheep perished by drowning. In 2002, Maltese-flagged Gotia rammed into the Emirgan Pier. The vessel leaked 25 tons of oil to the Strait [6].

## 1.2. Objectives of the Study

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

One important policy of the VTS is to have the vessels transiting the straits maintaining specific minimum distances between then, while different vessel types have different pursuit distance rules. Just as the VTS does, the simulation model also aims to apply the strict interval rules and moreover, using parametric distances among different vessel types, facilitates easy detection of the effects of altering pursuit distances over important performance measures like vessel waiting times and total number of vessels serviced and vessel density in Strait.

Another important issue considered by the VTS is the adverse meteorological conditions that sometimes lead to full or partial closure of the strait to maritime. The model also takes this fact into consideration and revises the daily traffic plan with respect to live prevailing meteorological conditions, therefore facilitating the observations of the effects of natural factors on performance measures and paves the way for risk analysis.

Pilotage and tugboat services in real situation are of great importance for a safer Strait transit. In order to diminish the waiting time of vessels due to the lack of these services, this study systematizes the pilot and tugboat necessities with regular availability checks.

On the other hand, the ultimate aim of this study is to provide modeling support to a comprehensive risk analysis study on the risks associated with the maritime traffic in the Strait of Istanbul. This is expected to be achieved by localizing the risk entertaining regions along the Istanbul Strait, while the development, calibration of the risk assessment model and its integration to the maritime simulation model is not attempted in this study.

Chapter 2 presents a literature survey about the studies on transportation modeling and risk analysis for waterways in the world and then in the Istanbul Strait.

In Chapter 3 the constructed simulation model is presented. In this context, the arrival process with classification of vessels according to their length, loads and passage directions, the mathematical model for daytime and nighttime traffic scheduling, the representation of pilot and tugboat services, meteorological restrictions, overtaking conditions are discussed.

The inputs and the outputs of the simulation model (together with the selected performance measures for output analysis) are presented and discussed in Chapter 4. Verification and validation of the developed simulation model including the design, execution and analysis of the simulation runs intended for verification purposes are also accomplished in Chapter 4.

Chapter 5 contains the scenarios analysis. The development of scenarios, key factors considered in these scenarios, scenario results and comparison of scenario results through factor analysis are discussed in this chapter.

The final chapter includes the conclusions and future studies, especially regarding the integration of the current study with a comprehensive risk analysis of the maritime risk in the Strait of Istanbul.

# 2. LITERATURE SURVEY

In this chapter other studies related to the objective and contents of this study are briefly introduced. The survey covers three types of studies, firstly, since the primary mathematical tool deployed in this study is simulation, other works primarily deploying simulation models (especially regarding maritime transportation issues) are presented. Next, since the ultimate aim of this study is to support risk analysis in the Istanbul Strait, other works on maritime risk analysis and integration of simulation and risk models are presented. Finally, other studies on the maritime traffic in the Strait of Istanbul are briefly introduced.

Mulherin et al. [7] develops a simulation model to estimate and investigate the maritime transit times between Murmansk and Bering Strait. They get the simulation runs for the most critical months of April, June, August and October. Meteorological conditions are the basic inputs in this study; however, due to the difficulty to access the actual data, they use Monte Carlo Simulation to estimate the transit times by randomly generating travel speeds in different environmental conditions. This model also estimates costs for transporting three types of loads and by modifying parameters, facilitates decision making in different scenarios.

Franzese et al. [8] present a simulation model designed in Arena software about the famous locks system, in the Panama Canal. The study considers vessel arrivals, traffic regulations and vessel pre-sequencing as input and does the experiments about the resources of the Canal and produces outputs such as queue length, waiting times at anchorages, transit times, number of transits and locks occupation. These experiments are also useful for new proposed locks.

Bruzzone et al. [9] develop an interactive and effective model for designing maritime infrastructure and harbors considering risk for routine activities and specific conditions like oil spill, fires and explosions. To perform risk assessment, they use a system called maritime environment for simulation analysis (MESA), an interactive tool that includes mapping, navigation and emergency information and estimates the results of undesired incidents especially oil spills. As an experiment, they dispose pollutants to sea and observe the movement of pollutants. They analyze effects of five variables namely, wind direction, wind intensity, activation time of containment devices, effectiveness of containment devices, and dimension of containment devices, on the total quantity of pollutant material that reached the coast using design of experiments methodology (DOE).

Merrick et al. [10] analyze the Washington State Ferries and build a risk simulation model for accidents based on available data and expert judgments. They identify the dynamic environment of risk elements, such as low visibility, wind conditions and traffic interactions. Moreover, Merrick et al. [9] create a simulation model in order to analyze effects of visibility and ferry service increase in the San Francisco Bay. While building the visibility model Analytical Hierarchy Process (AHP) methodology is used in order to compile input data related to expert opinion.

Yurtören and Aydoğdu [11] present a study on the risk assessment, for the local traffic in Istanbul Strait. They use the Environmental Stress Model, which comprehends traffic, environmental, physical conditions and human factors and numerically estimates the amount of risk. The results show that local traffic has a significant influence increasing the likelihood and consequences of major accidents involving transit vessels (especially tankers) and the local traffic management is inevitable for a less risky Strait traffic.

Köse et al. [12] build a simulation model of the maritime traffic in the Istanbul Strait that reflects the actual traffic flow regarding the R&R, by the software AWESIM. Traffic flow from both directions, two information systems representing large vessels and bad weather conditions are modeled and future traffic behavior is estimated according to the several scenarios such as increasing the tanker traffic frequency.

Özbaş [1] designs a comprehensive simulation model that takes R&R, vessel attributes, arrival rates, meteorological factors like fog, wind, current and pilotage and tugboat services into account, using software Arena. This model facilitates the analysis of performance measures and comparison of the said factors, identifying their interactions. Most of the input data are gathered from the VTS authorities. The main performance measures are average waiting time of vessels before entering to Strait, maximum waiting times, transit times, density of vessels on the Strait and pilot and tugboat utilizations.

Mavrakis and Kontinakis [13] present a queuing model with ANSI C for the Istanbul Strait that lists vessels according to their loads, giving highest priority to passenger vessels, followed by general cargo ships and tankers respectively and allows the vessels, satisfying the necessary conditions (which are mostly based on regulations and weather conditions) to enter. Vessel interarrival distributions are based on vessel length and load. Scenarios are generated with respect to vessels arrival rate and vessel attributes. Accident occurrences are also added as the effective factor affecting the availability of the system.

Almaz [2] develops a Maritime Traffic Simulation Model consisting of a visibility submodel, a current submodel and an arrival process submodel. The actual vessel movements are based on the updated R&R. The software used is Arena 9.0. Data for interarrival time of vessels are gathered from year 2005, fog durations are estimated by empirical and “Mixtures of Generalized Erlang” distributions. This study includes a detailed scenario analysis of 64 alternatives, by altering arrival rate, number of pilot or tugboat services, vessel profile, current pattern, pursuit distance and season factor. Results show that pursuit distance is the most significant factor for most of the performance measures.

Or et al. [14] enhance the previous studies and build a new simulation model with Arena 9.0. in parallel with revisions of the R&R in Istanbul Strait traffic plan. The main difference from the earlier models is in the representation of traffic flows based on the new regulation that has been but put into effect after 2005. According to the new regulations, the VTS allows only uni-directional passage in daytime and opens both direction entrances at night instead of bi-direction traffic for the whole day and this causes changes in the traffic plan. In the study, vessel transit rules are converted into simulation language as model inputs and pursuit distance among each type of vessel and traffic flow window sizes for each predetermined direction and pilot and tugboat supports are reviewed. To mimick the real traffic system in the Strait, overtaking, visibility and current submodels are integrated to the model, as well. Scenario analysis not only facilitates to understand the effects of inner and external factors on the Strait traffic, but it also provides an opportunity to compare the updated model with the previous studies.

Ulusçu et al. deal with the scheduling of daytime and nighttime traffic plan after the recent changes in regulations. They assign different weights to each type of vessel, giving preference to large hazardous cargo vessels and tankers and define an algorithm that decides the first direction to be opened in daytime. Another formulation determines how many class A and B (i.e. most troublesome) vessels should pass from the Strait during calculated time windows of each direction. Vessels wait in their individual queues (based on their types) to enter to Strait according to the highest waiting time and until other external conditions (meteorological, visibility and pilot and tugboat needs) are satisfied.

# 3. THE SIMULATION MODEL OF THE MARITIME TRAFFIC IN THE STRAIT OF ISTANBUL

The simulation model, developed in Arena 11.0 software, gives due consideration to the actual maritime traffic activity in the Istanbul Strait with regard to the 2009 data obtained from the VTS. Through the input analysis, appropriate probability distributions of interarrival times of vessels arriving at the Istanbul Strait are determined. Then, within the simulation model, likely vessels are randomly generated based on the determined arrival distributions. The daily visibility and current conditions of 2009 are inputted to the model from external files in order to reflect the likely traffic flow under realized meteorological conditions.

Vessels enter the Strait either from north, (traveling south and thus are called as southbound vessels) or from south (traveling north and thus are called as northbound vessels). Since 2005, in the Strait of Istanbul vessel traffic flows in one direction (either northbound or southbound, in their respective and consecutive time windows) during daytime, while both way passage is allowed through nighttime. The timing and duration of the northbound and southbound traffic windows are also determined by the VTS based on number of vessels waiting in queues and their waiting time. The simulation model on the other hand, systematizes these durations based on estimates regarding the number of vessels planned to be pass from each side, while deciding the first direction of daytime traffic by considering the number of vessels in queues and their waiting times (in a manner mimicking similar decision making at the VTS).

In addition to the arrival process and scheduling decisions, this study also considers all causes banning vessel admissions to the Strait (thereby causing to vessel queues), such as entering rules based on vessel classes, minimum pursuit distance satisfactions, obstructive visibility and current conditions and pilot and (or) tugboat availabilities; the model also includes vessel overtaking activities and pilot and tugboat transfers from each direction.

### 3.1. Vessel Classification

The VTS has a specific vessel classification system covering all vessels requesting transit through the Istanbul Strait. This system is based on

(i) Vessel types and cargo characteristics which is set to be one of,

- Tankers;
- LPG-LNG carrying vessels;
- Hazardous material carrying vessels;
- Dry cargo vessels;
- Passenger vessels.

(ii) Vessel lengths which is set to be one of,

- Less than 50 meters;
- Between 50 meters and 100 meters;
- Between 100 meters and 150 meters;
- Between 150 meters and 200 meters;
- Between 200 meters and 250 meters;
- Between 250 meters and 300 meters;
- Longer than 300 meters.

The complete vessel classification based on these properties is displayed in Figure 3.1.

<table>
<tr><th></th><th></th><th colspan="5">Type</th></tr>
<tr><th>Length (m.)</th><th>Draft (m.)</th><th>Tanker</th><th>LNG-LPG</th><th>Carrying Dangerous Cargo</th><th>Dry Cargo</th><th>Passenger Vessels</th></tr>
<tr><td>< 50</td><td>< 15</td><td rowspan="2">Class E</td><td rowspan="3">Class C</td><td rowspan="2">Class E</td><td rowspan="3">Class D</td><td rowspan="6">Class P</td></tr>
<tr><td>50 - 100</td><td>< 15</td></tr>
<tr><td>100 - 150</td><td>< 15</td><td>Class C</td><td>Class C</td></tr>
<tr><td>150 - 200</td><td>< 15</td><td colspan="3">Class B</td><td rowspan="3">Class C</td></tr>
<tr><td>200 - 250</td><td>< 15</td><td colspan="3" rowspan="2">Class A</td></tr>
<tr><td>250 - 300</td><td>> 15</td></tr>
<tr><td>> 300</td><td>> 15</td><td colspan="5">Class T6</td></tr>
</table>

Figure 3.1. Categorization of vessels

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

Class A and T6 vessels are the most critical vessels among all types in terms of the risks they generate. They are allowed to enter the Strait only in daytime and are expected not to encounter any opposite traffic flow during their transit. Class B vessels are also of considered critical in that they are also expected not to encounter any opposite traffic flow during their transit but they are allowed to enter the Strait at nighttime, as well as daytime (naturally, their daytime passage have lower priority than that of Class A and T6). For scheduling which will be discussed in detail, Class C has priority over Class D and E, while Class E has supremacy over Class D. Class P vessels carry passengers and therefore they have top priority in admission to the Strait (i.e. they are placed at the top of waiting queue regardless of their waiting time). Nevertheless, all vessels may only be admitted to the Strait after the satisfaction of their “pursuit distance/time” requirements regarding preceding vessels already in the Strait, regardless of their priority status.

## 3.2. Data Description

Basic inputs of the simulation model such as individual vessel’s arrival time, age, type, length, cargo, stopover or non-stopover passing status, speed, pilot and tugboat needs, anchorage duration and ready time information) are randomly generated based on distributions fitted to the real data of year 2009 at the VTS. According to this, vessel type AN means an A type northbound vessel and AS means an A type southbound vessel. Total number of vessels passed in 2009 is 51422 and the majority is general cargo vessels designated as Class D (Table 3.1).

Table 3.1. Number of vessels passed over the Strait in 2009

| Vessel type | Number of vessels passed |
|---|---|
| AN | 1156 |
| AS | 1105 |
| BN | 1514 |
| BS | 1430 |
| CN | 4931 |
| CS | 5023 |
| DN | 16739 |
| DS | 16431 |
| EN | 840 |
| ES | 938 |
| PN | 659 |
| PS | 656 |
| **Total** | **51422** |

Some other statistics from the VTS data are as follows:

- 22.76 % of vessels prefer to anchor;
- 50.25 % of total are northbound vessels;
- 48.56% of total demand pilot;
- Only 1.46 % of vessels demand tugboat;
- Actual speed during passage is 10.5 knots on the average while reported one is 10.7 knots.

### 3.3. The Istanbul Strait Traffic Rules and Regulations

Vessels arriving at the Istanbul Strait comply with the scheduling and navigation decisions of the VTS. Instead of following the simple “first come, first served” rule, the VTS orders vessels according to their cargo types, draft and length and assigns them various priorities. In addition to ranking vessels, VTS attends to regulations, pursuit distance requirements, safe meteorological conditions, and pilot and tugboat availabilities and in case of non-satisfaction of any of the related conditions vessels keep on waiting in queue. Some of the rules related to vessel transit planning that are also reflected in the simulation model are as follows:

- The minimum distance between two consecutive vessels entering the Strait should be at least 8-cables distance (1.09 miles) between each other.

This rule is usually implemented by requiring at least a 10 minute interval (corresponding to 8 cables at an average speed 10.5 of knots) between two consecutive ready to enter vessels from one direction.

- Tankers and vessels carrying dangerous cargo or LNG-LPG with length longer than 200 meters and those carrying dry cargo and passenger vessels longer than 300 meters should transit during daytime.

It is compliance to this rule that Class A and T6 vessels pass through the Strait only through daytime. Any vessels in this group cannot be part out of the nighttime traffic plan. This vessel class also forms the basis of the daytime schedule in this study, due to its high priority.

- During their passage through the Istanbul Strait, tankers and vessels carrying dangerous cargo or LNG-LPG with length more than 250 meters should not come up against any type of vessel except passenger vessels.

It is because of this rule that bi-directional traffic during daytime is almost impossible to manage and therefore single directional time windows are preferred.

- Vessels carrying dangerous cargo, regardless of their length, should not come across with dangerous cargo or LNG-LPG carrying vessels and tankers with length between 200 and 250 meters.

In other words, Class E and C vessels are not allowed to meet with Class A which is resolved by the unidirectional daytime traffic, as well.

- Dangerous cargo carrying vessels longer than 200 meters should not come across with dry cargo carrying vessels longer than 150 meters and vice versa.

According to this rule the encounter of Class A and T6 vessels with Class C longer than 150 meters is prohibited.

- LNG-LPG or dangerous cargo carrying vessels regardless of their lengths should not come across with any other dangerous cargo or LNG-LPG carrying vessels nor with tankers longer than 100 meters.

This regulation marks out the nighttime bi-directional flow schedule and implies that even Class B, C and E vessels should not meet each other.

- Dangerous cargo or LNG-LPG carrying vessels or other vessel types longer than 150 meters should not come across with tankers dangerous cargo and LNG-LPG carrying vessels with length between 100 and 150 meters and general cargo carrying vessels longer than 150 meters between Kanlıca – Vaniköy.

Kanlıca – Vaniköy is the narrowest region in the Strait. This rule prevents the meeting of large vessels in this region to minimize the collision risk; therefore in this study, overtaking is not allowed in this region.

- Dangerous cargo, LNG-LPG carrying vessels or tankers longer than 200 meters should enter the Istanbul Strait after the preceding such vessel ahead and moving in the same direction have passed the Filburnu (in northbound traffic flow case) or the Boğaziçi Bridge(in southbound traffic flow case).

This rule is generally implemented by requiring a time interval of at least 75 minutes between two consecutive southbound Class A vessels and at least 90 minutes between two consecutive southbound Class A vessels.

- A southbound stopover vessel has priority over a northbound stopover vessel, which has priority over any non-stopover vessel.

The VTS implements this regulation by multiplying realized waiting times of vessels with different weights (all greater than or equal to one). Then queues of vessels are ordered with respect to these adjusted waiting times.

### 3.4. The Arrival Process of Vessels

Vessels are obliged to submit SP-2 reports at least two hours or 20 nautical miles (whichever first) before their arrival at the Strait. Vessels requesting immediate Strait transit on arrival in their SP-2 reports are treated as “ready to enter” and placed to their respective queues as soon as they arrive, while vessels requesting a certain stopover time (for supplies or other purposes) in their SP-2 reports are routed to anchorage area to have their “ready to enter condition” initiated after their stopover needs and duration is covered.

Initial observations of the actual arrival data of around 51,000 vessels in 2009 considered in this study have indicated that different vessel types have dissimilar interarrival patterns. Accordingly, in this study vessel interarrival times are fitted different interarrival time probability distributions based on vessel classification and direction. Time of submitting SP-2 report is the input data used for determining interarrival distributions of vessels classes. 6 distinct interarrival distributions have been deployed in each direction.

The Arena Input Analyzer module which is a very efficient tool for distribution fitting to data is deployed in fitting interarrival time distributions. Via the Input Analyzer’s Fit menu, all probable distributions fitted to the actual data are revealed and “fit all” property estimates the distribution with the minimum square error. After fitting a distribution, a histogram and the probability density function (pdf) superimposed on the histogram summarize the characteristics of the fit [16].

Goodness-of-fit hypothesis tests are used to evaluate whether the fitted distribution is a good fit or not to the actual data. Arena Input Analyzer utilizes two tests, chi-square and Kolmogorov- Smirnov (K-S) tests. The chi-square test compares the empirical histogram pdf or probability mass function (pmf) with the theoretical one and needs large number of data for a smoother histogram. The Kolmogorov-Smirnov (K-S) test on the other hand, compares the empirical cumulative distribution function (cdf) with the theoretical cdf and needs no histogram, so may work with fewer data [16]. In order to assess the appropriateness of the fitted distrbiution, p-values of the tests are used. The term p-value of a data set in a test is the "probability of getting a data set through the fitted distribution that is more inconsistent with the data set on hand, if the fitted distribution is truly the "the truth". The other term significance level α or type I error is the probability of rejecting the null hypothesis ($H_0$) where it is actually true. Here,

(i) $H_0$: candidate distribution is a sufficiently good fit to the data

(ii) $H_1$: candidate distribution is not a good fit

In these tests, when p-value is less than significance level $\alpha = 0.05$, it is deducted that the considered probability is not a good fit, although higher value is not a solid proof that the distribution fits well [17].

To illustrate, consider the interarrival time distribution of northbound Class E vessels. There are 839 interarrivals in the 2009 data for this vessel class and the best fitted distribution is found as the Gamma distribution with shape parameter α being 648 and scale parameter β being 0.974. In the summary report of Arena Input Analyzer (as displayed in Figure 3.2), the shape of the probability density function overlaps with the histogram and just looking at this figure, one gets the feeling that the selected function represents the actual interarrival time data quite well.

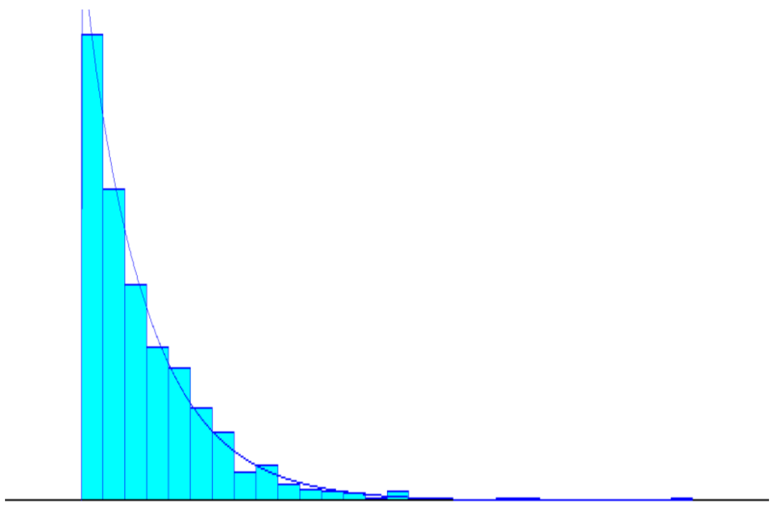

Figure 3.2. Histogram of northbound Class E interarrivals

To be more precise, Figure 3.3 denotes the name and parameters of the distribution while checking it with both hypothesis tests. The hypothesis tests have both p-values higher than 0.05, which is taken as an indication of interarrival distribution being an acceptable fit.

```
Copy
        Distribution Summary

Distribution:   Gamma
Expression:     GAMM(648, 0.974)
Square Error:   0.000507

Chi Square Test
  Number of intervals   = 12
  Degrees of freedom    = 9
  Test Statistic        = 8.51
  Corresponding p-value = 0.487

Kolmogorov-Smirnov Test
  Test Statistic        = 0.0301
  Corresponding p-value > 0.15

        Data Summary

Number of Data Points   = 839
Min Data Value          = 0.417
Max Data Value          = 6.02e+003
Sample Mean             = 631
Sample Std Dev          = 639

        Histogram Summary

Histogram Range         = 0 to 6.02e+003
Number of Intervals     = 28
```

Figure 3.3. Distribution summary for northbound Class E interarrivals

Figure 3.4 displays the square errors of various density functions that are tested for the indicated dataset. The top most function is the best fitting one, and has the least square error. The second one is the exponential distribution and has the same error with the next in line Erlang distribution both distributions also provide good fits and feature error terms comparable to the Gamma distribution.

```
Fit All Summary
Data File: C:\Users\SIRIN\Desktop\E_N3.dst.txt


Function       Sq Error
-----------------------
Gamma          0.000507
Exponential    0.000542
Erlang         0.000542
Weibull        0.000553
Beta           0.00163
Lognormal      0.00714
Normal         0.0511
Triangular     0.0978
Uniform        0.134
```

Figure 3.4. Square errors for northbound Class E interarrival time distributions

Since classification is based on length, cargo type and direction of vessels, for a detailed analysis, vessels are subcategorized depending upon these properties and their attributes are also estimated through the Input Analysis. As an example, southbound C is divided into the following 7 subclasses:

- General Cargo with length 150-200 meters;
- General Cargo with length 200-250 meters;
- General Cargo with length 250-300 meters;
- Hazardous material with length 100-150 meters;
- LPG-LNG with length 0-100 meters;
- LPG-LNG with length 100-150 meters;
- Tanker with length 100-150 meters.

Appropriate probability distributions for average speed for each of these subclasses are generated through the Arena Input Analyzer. The fitted distributions for all vessel classes are displayed in Appendix A.

Next, for each vessel subclass its anchorage duration is generated based on the realized anchorage durations of the related vessels (as reported in their SP-2 reports). The appropriate probability distributions regarding the anchorage durations are again fitted through the Input Analyzer.

Similarly, pilot and tugboat demand and stopover vessel rates deployed in the simulation model for each subclass are based on empirical probability distributions obtained from the related 2009 data (these are deployed in Appendix A).

Vessel lengths within each subclass are assumed to be uniformly distributed in order to comply with the aforementioned vessel classification. Lower and upper bounds are the length intervals of these classifications. As a demonstration of placing attributes, determined as described in the above paragraphs, the case of “southbound Class A” is displayed in Figure 3.5. As can be seen from the classification (in Figure 3.1.), there are 5 subclasses, such as tankers between 200 and 250 meters length and between 250 and 300 meters length, LPG-LNG carrying vessels between 200 and 300 meters length, Hazardous material carrying vessels between 200 and 250 meters length and between 250 and 300 meters length. Among these groups, tanker with 200-250 meters vessel class has the largest percentage among others (66 %). Pilot percentage of this group is 99.60, tugboat percentage is only 0.522, while nonstop over passing vessels constitutes 3.16 percentage of all and average speed is conformed to NORM (12.1, 1.08) nautical miles.

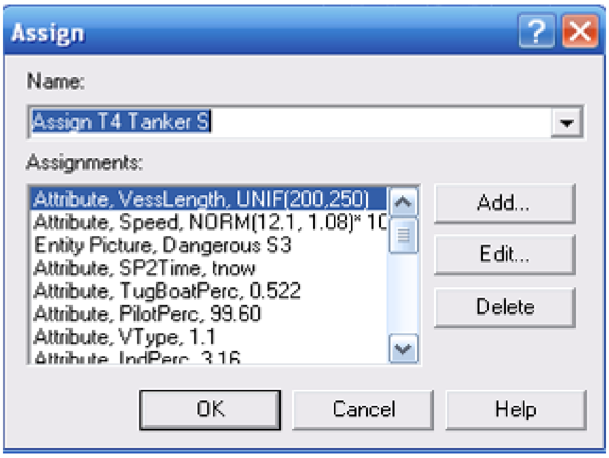


Figure 3.5. Assign module of southbound Class A Tanker

### 3.5. The Arrangement of Pursuit Distances

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

Let θ be the minimum pursuit distance between two consecutive vessels of class D, E, P traveling northbound and let μ be the minimum pursuit distance between two consecutive vessels of class D, E, P traveling southbound. Then,

(i) The minimum pursuit distance between a northbound (southbound) class D, E or P vessel and a class A, B or C vessel sailing in the same direction is also θ (μ).

(ii) The minimum pursuit distance between two consecutive class C vessels traveling northbound (southbound) is 2*θ (2* μ) and the minimum pursuit distance between a northbound (southbound) class C and a class A or B vessel sailing in the same direction is also 2*θ (2* μ).

(iii) The minimum pursuit distance between two consecutive A and B vessels traveling northbound (southbound) is respectively 6*θ (6* μ) and 4*θ (4* μ).

Assuming an average vessel speed of 10.5 knots, the VTS would ideally like to implement θ and μ as 14 minutes and 12.5 minutes respectively. However depending on vessel arrivals, congestion, weather and sea conditions (as well as risk perceptions of individual on duty VTS operators) θ is implemented between 10-15 minutes and μ is implemented between 9-14 minutes. This approach of the VTS regarding pursuit distances is also reflected in the simulation model, while the value of θ and μ deployed in the base scenario is determined through a calibration process described in Chapter 4.

The primary difference of the simulation model developed in this study and in a previous study [15] is in the key issue of the arrangement and treatment of vessel sequences to enter the Strait. As explained in the previous paragraph, in the current model the parametric minimum pursuit distance accepted (such as θ or μ) defines the time slots for vessels to be let into the Strait. When a time slot is realized, all eligible (waiting) vessels are considered in the explained priority order and just the "minimum pursuit distance" requirement of the candidate vessel with the existing (transiting) vessel in the Strait are checked. In the [15] simulation model, the sequence of vessels to enter the Strait is predetermined (in line with the minimum pursuit distance requirements) and rigid (such as an A vessel followed by 2 D vessels, followed by a C vessel followed by 2 more D vessels, followed by another C vessels and so on). This approach necessitates a complex system of "tentative queues", difficulties in updating and revision and considerably limits vessel alternatives when a slot is realized during the simulation time clock. In the approach undertaken in this study, all such problems are eliminated.

### 3.6. Daytime Vessel Scheduling

In the daytime vessel traffic plan, the VTS sets the time and duration of the daily uni-directional time windows (which also determine the number of vessels to be serviced in those time windows, based on the pre-determined pursuit distances). In this study, daytime traffic flow is systematized with a mathematical model reflecting the R&R, service availabilities and meteorological constraints in mind.

The maximum flow length of daytime in minutes and start time of the daytime traffic differ according to seasons as depicted in Table 3.2. The model, as the VTS does, plans the daytime schedule at 5.00 a.m. in the morning in winter time and as indicated in Table 3.2 in other seasons.

Table 3.2. Start time and maximum traffic duration in different seasons

| **Season** | **Start Time($t_s$)** | **Max. Duration (DT)** |
|---|---|---|
| WINTER | 7:00 | 615 |
| SPRING | 6:30 | 735 |
| SUMMER | 6:00 | 855 |
| AUTUMN | 6:30 | 735 |

The first direction of vessel flow into the Strait of Istanbul is determined based on the total number of vessels in queues and their waiting time. The formula used for in the determination of starting direction is as follows:

$$S^d = a * \frac{Ca * NQ(A)^{(d)} + Cc * NQ(C)^{(d)} + Cd * NQ(D)^{(d)} + Ce * NQ(E)^{(d)}}{NQ(A)^{(d+d')} + NQ(C)^{(d+d')} + NQ(D)^{(d+d')} + NQ(E)^{(d+d')}}$$
$$+ b * \frac{Ca * WT(A)^{(d)} + Cc * WT(C)^{(d)} + Cd * WT(D)^{(d)} + Ce * WT(E)^{(d)}}{WT(A)^{(d+d')} + WT(C)^{(d+d')} + WT(D)^{(d+d')} + WT(E)^{(d+d')}} \quad (3.1)$$

where:

$S^d$ : score value of the active direction *d*

$S^{d'}$: score value in the opposite (passive) direction *d'*

$a$ : multiplicative constant for number of vessels in queues

$b$ : multiplicative constant for waiting time of vessels in queues

$Ca$ : coefficient for A type vessels

$Cc$ : coefficient for C type vessels

$Cd$ : coefficient for D type vessels

$Ce$ : coefficient for E type vessels

$NQ(i)_{t_s}^{(d)}$ : number of i type vessels in queue in active direction *d* at time t=$t_s$

$NQ(i)_{t_s}^{(d')}$ : number of i type vessels in queue in passive direction *d'* at time t=$t_s$

$WT(j)_{t_s}^{(d)}$ : total waiting time of j type vessels in active direction *d* at time t=$t_s$

$WT(j)_{t_s}^{(d')}$ : total waiting time of j type vessels in passive direction *d'* at time t=$t_s$

This formula is applied for both directions and the direction with higher score is declared as the starting direction of the daytime traffic schedule. Two significant factors influencing the determination of the first direction of daytime flow are the number of vessels in queues and vessel waiting times and they are in different level of significance. (The associated weights α and b are nominated as 0.25 and 0.75 respectively). The other coefficients are related to vessel types. Since Class A vessels have the longest pursuit distances and highest priorities in daytime schedule, they get the highest value. The values of vessel type coefficients are displayed in Table 3.3. Passenger vessels are excluded in this comparison since Class P may enter the Strait in both directions whenever meteorological conditions and pilot or tugboat necessities are satisfied. Class B is also ignored because it is not allowed to enter the Strait during daytime.

Table 3.3. Values of vessel class priority scores

| Coefficient | Value |
|---|---|
| *Ca* | 0.5 |
| *Cc* | 0.3 |
| *Cd* | 0.1 |
| *Ce* | 0.1 |

In order to set out the framework for daytime schedule, after attaining the first direction of daytime traffic, number of Class A transiting from both directions are estimated. In this respect, maximum daytime duration (*DT*) is divided in proportion to the number of vessels in northbound and southbound queues.

Starting direction traffic time window length is calculated as:

$$W_d = \frac{NQ(A)_{t_s}^{d}}{NQ(A)_{t_s}^{d} + NQ(A)_{t_s}^{d'}} \tag{3.2}$$

Opposite direction traffic time window length is calculated as:

$$W_{d'} = \frac{NQ(A)_{t_s}^{d'}}{NQ(A)_{t_s}^{d} + NQ(A)_{t_s}^{d'}} \tag{3.3}$$

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

$$N_p(d) = \frac{W_d}{6 * \delta(d)} \tag{3.4}$$

where:

$$\delta(d) = \begin{cases} \theta & if \ d \ is \ northbound \\ \mu & if \ d \ is \ southbound \end{cases} \tag{3.5}$$

The parameters in the denominator changes with regard to starting direction decision. The number of Class A vessels planned to enter the Strait during the opposite direction vessel traffic flow is:

$$N_p(d') = \frac{W_{d'}}{6 * \delta(d')} \tag{3.5}$$

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

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

$$W_j^a = c * WT_{t_s}^d(j) \tag{3.6}$$

where:

$$c = \begin{cases} 1.5 & \text{Vessel j is a southbound stopover vessel} \\ 1.25 & \text{Vessel j is a northbound stopover vessel} \\ 1 & \text{Otherwise} \end{cases} \quad (3.7)$$

At the daytime traffic start time, for each time slot (regarding entrance to the Strait), the model considers the queues of vessel classes in the designated direction in the order identified by vessel priorities and checks each queue, (which is ordered with respect to elapsed waiting time), until an appropriate vessel (regarding pursuit distance requirements related to vessels already in the Strait) is identified. That vessel is removed from its queue and entered into the Strait.

As mentioned before, passenger vessels have the highest priority in vessel sequencing. So, the model first searches the Class P queue in the determined direction (*d*). If there exists any P vessels in the determined direction and if the visibility conditions and pilot and tugboat demand are satisfied, the one having the maximum elapsed waiting time is allowed to the Strait and the time is incremented as $\theta$ ($\mu$) minutes. Meanwhile, if there exists any P vessels on the other side, the one with the maximum elapsed waiting time is allowed to the Strait as well (even though a uni-directional time window is in action). If there is not any P vessel in the determined direction, the model searches the Class A queue. If there is any A type vessel in the determined direction, then the pursuit distance requirements, meteorological situations and pilot and tugboat availabilities are checked. When all conditions are fulfilled, the class A vessel having the maximum elapsed waiting time enters the Strait, otherwise model examines the Class C, E and D vessel queues respectively and allows the one having maximum elapsed waiting time regarding their minimum pursuit distances among class types. As soon as a vessel enters the Strait, again time is increased as the minimum pursuit distance interval (as $\theta$ or $\mu$ minutes) and the other distance rules among vessel types are also checked (i.e. $2*\theta$ ($2*\mu$) minutes between two consecutive C vessel, $6*\theta$ ($6*\mu$) minutes between two consecutive A vessels have to be met) until the last planned A vessel with the maximum elapsed waiting time in the active direction enters the Strait.

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

$$ST = MAX(0, DT - (\bar{t} - t_s + W_{d'})) \tag{3.7}$$

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

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

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

$$NQ_{\bar{t}}(A)^{d'}_{SLACK} = MAX(0, (NQ(A)_{\bar{t}}^{d'} - N_p(d'))) \tag{3.8}$$

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

$$WT(A)^{d'}_{SLACK} = WT(A)^{(d')} - WT(A)^{d'}_{t_s} \tag{3.9}$$

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

$$X = \frac{NQ(A)^{(d)}}{NQ(A)^{d'}_{SLACK}} \tag{3.10}$$

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

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

$$Y = \frac{WT(A)^{(d)}}{WT(A)^{d'}_{SLACK}} \tag{3.11}$$

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

(vi) The indicator $Z$ is determined as follows:

$$Z = X * \alpha + Y * b \tag{3.12}$$

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

a. If Z is greater than or equal to 1, it is deduced that the additional class A vessel (planned to pass in the slack time) should be a *d*-directional vessel and then the equations 3.10 and 3.11 are updated. Number of *d*-directional planned A vessels in slack time ( $N(d)^{SLACK}_{p}$ ) is incremented by one.

$$N(d)^{SLACK}_{p} = N(d)^{SLACK}_{p} + 1 \tag{3.13}$$

and the slack time length is updated as:

$$ST = ST - 6 * \delta(d) \tag{3.14}$$

b. If Z is less than 1, it is deduced that the additional class A vessel (planned to pass in the slack time) should be a *d'*-directional vessel and then the equations 3.10 and 3.11 are updated. Number of *d'*-directional planned A vessels in slack time ( $N(d')^{SLACK}_{p}$ ) is incremented by one and the slack time length is updated same as equation 3.14.

$$N(d')_p^{SLACK} = N(d')_p^{SLACK} + 1 \tag{3.15}$$

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

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

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

The start and execution of the vessel traffic flow in the opposite direction (d') traffic is same as the first direction flow. Vessels are allowed to the Strait until reaching the number of planned A vessels in direction d'. If slack time algorithm determines any more A vessels in this direction, they also enter the Strait until the strait of the nighttime vessel traffic. A typical representation of a daytime schedule is depicted in Figure 3.6.

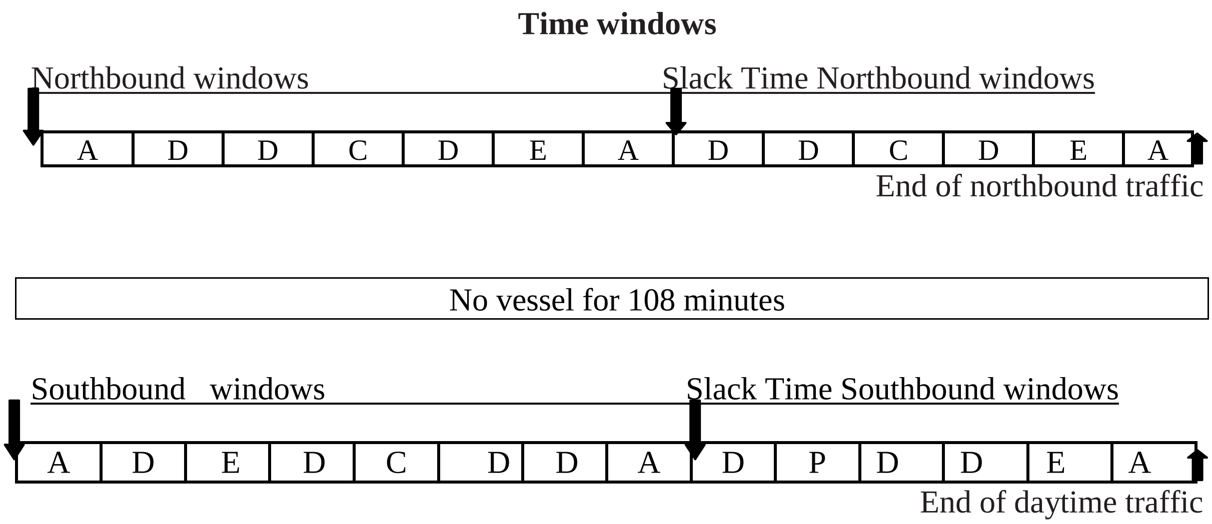


Figure 3.6. An example for daytime schedule

### 3.7. Nighttime Vessel Scheduling

Nighttime traffic plan is dissimilar from daytime vessel schedule in many respects. When daytime traffic ends, the last traffic flow direction remains as the first direction of nighttime traffic (therefore, the determination of the nighttime flow starting direction becomes unnecessary). Additionally, unlike daytime uni-directional traffic, at nighttime, there exists two restricted vessel flows (the term restricted is emphasized since according to the R&R, only Class D vessels may enter from the opposite direction when there are such vessels available at their queues and meteorological conditions allow).

Presuming Class B as the superior group (with regard to its higher priority among other types) in the nighttime schedule, the length of northbound and southbound time windows are outlined by class B (similar to the standing Class A in daytime scheduling). This is because in nighttime, Class B vessels are critical in that they must not meet any other vessel during their Strait transit. Moreover, the abundance of Class C vessels of 2009 VTS data (around 9000 class C vessels in a year) compels to take this class into account while designing the nighttime traffic plan. Considering that minimum pursuit distance between two class B vessels is 4*$\theta$ (4*$\mu$) whereas minimum pursuit distance between a class B vessel and a class C vessel is 2*$\theta$ (2*$\mu$), the duration of nighttime restricted traffic flow time is determined by the number of planned Class B vessels (multiplied by 2*$\theta$ or 2*$\mu$, according to active direction), and the number of remaining class C vessels (multiplied by $\theta$ or $\mu$, according to active direction).

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

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

$$NQ_{t_n}^{\ d'}(B_{up}) = NQ_{t_n}^{d'}(B) + MAX(0,(NQ_{t_n}^{d'}(C) - (NQ_{t_n}^{d'}(B)-1))/2) \qquad (3.16)$$

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

$$NW_p(d) = NT * \frac{NQ_{t_n}^{d}(B_{up})}{NQ_{t_n}^{d}(B_{up}) + NQ_{t_n}^{d'}(B_{up})} \tag{3.17}$$

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

$$NW_p(d') = NT * \frac{NQ_{t_n}^{d'}(B_{up})}{NQ_{t_n}^{d}(B_{up}) + NQ_{t_n}^{d'}(B_{up})} \tag{3.18}$$

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

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

$$N_p^B(d) = \min(NQ_{t_n}^{d}(B), \frac{NW_p(d)}{4*\delta(d)}) \tag{3.19}$$

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

$$N_p^B(d') = \min(NQ_{t_n}^{d'}(B), \frac{NW_p(d')}{4*\delta(d')}) \tag{3.20}$$

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

$$N_p^{(C)}(d) = \max(0, \frac{NQ_{t_n}^{d}(C) - (N_p^B(d) - 1)}{2}) \tag{3.21}$$

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

$$N_p^{(C)}(d') = \max(0, \frac{NQ_{t_n}^{d'}(C) - (N_p^B(d') - 1)}{2}) \quad (3.22)$$

Both equations (3.21) and (3.22) are rounded down to nearest integer numbers.

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

$$NW(d) = \min(NW_p(d), N_p^B(d) * 4 * \delta(d) + N_p^C(d) * 4 * \delta(d)) \quad (3.23)$$

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

$$NW(d') = \min(NW_p(d'), N_p^B(d') * 4 * \delta(d') + N_p^C(d') * 4 * \delta(d')) \quad (3.24)$$

At nighttime, the first vessel entering the Strait follows the minimum pursuit distance between the last vessel of the daytime flow in the same direction. That is, if the last entering vessel at daytime traffic is a northbound class A vessel, then the first vessel at the nighttime schedule is either a northbound P, D or an E class vessel, since the minimum pursuit distance rule does not permit a B or C class vessel into the Strait at that time. Additionally, Class D vessels from the opposite direction are also admitted to pass at the minimum pursuit distance ($\theta$ or $\mu$ minutes between each D class vessels) intervals. After the last scheduled number of Class B vessel in the first direction of nighttime enter the Strait, in the remaining time period at this active direction, Class C vessels (and the other vessel classes among this class) are admitted to the Strait. Vessel transits from both directions flow until attaining $min(N_p^{(B)}(d) + N_p^{(C)}(d), NW(d))$ at the nighttime active direction.

The opposite direction traffic flow allowing Class B vessel to the Strait is initiated once the last Class B or C (whichever passes later) from the first direction leaves the Strait. At all time class D, E, P vessels from both directions are admitted into the Strait (regarding just minimum pursuit distance and meteorological conditions). Since it takes approximately 30 minutes for a class B at Filburnu (in northbound traffic flow case) or at Boğaziçi Bridge (in southbound traffic case) to completely exit the Strait, the time gap between the last northbound or southbound Class B vessel and the following vessel from the opposite direction should be 4* $\theta$ +30 or 4* $\mu$ +30 minutes, respectively. This direction flow is just same as the previous traffic flow and continues until reaching *min* ( $N_p^{(B)}(d') + N_p^{(C)}(d')$ , $NW(d')$) at the nighttime active direction.

Once the scheduled transit of Class B and C vessels is completed, if there is remaining nighttime, Class D and E vessels continue entering the Strait from both directions (with Class E still having higher priority) according to the minimum pursuit distances ($\theta$ or $\mu$) rules. During the schedule of next day daytime vessel traffic, based on the estimated starting direction of daytime, Class D and E vessels enter the Strait during this two hours planning period from the determined active direction of next day daytime flow. A typical representation of a nighttime schedule is depicted in Figure 3.7.

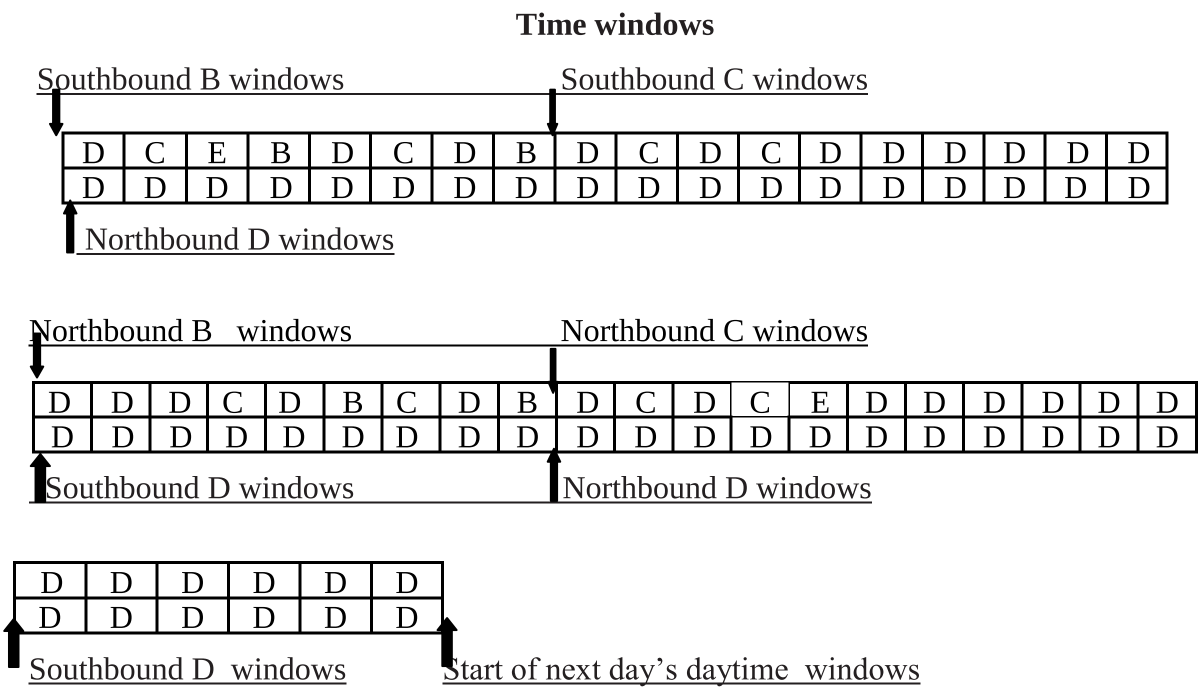


Figure 3.7. An example for nighttime schedule

## 3.8. Pilot and Tugboat Services

Pilot and tugboat services are of vital importance for safe navigation in the Strait. According to the R&R, having a pilot captain on board during the Strait passage is compulsory for vessels longer than 250 meters and optional (though strongly recommended) for other vessels. All vessels express their pilot captain and tugboat needs in their SP-1 and SP-2 reports. Pilots embarking and disembarking area is around the line connecting the Hamsi Limanı and Fil Burnu Lights at the Black Sea entrance and around Salacak at the Marmara Sea entrance [16]. There are 20 pilots and 6 tugboats available in real situation.

In the simulation model pilots and tugboats are treated as resources which are seized by vessels at the embarking area in the Strait and released while leaving. In order to meet pilot and tugboat needs, a control mechanism is built. Every hour the model searches the number of available pilots (including transferring pilots) in the active direction (i.e. at Hamsi Limanı during the southbound window and at Salacak during the northbound window) and requests pilots from the opposite side when it is less than 6. This query stops at the last hour of the time window since the transfer of a pilot to opposite side lasts about one hour. In order to make sure that Class A vessels' pilot needs are satisfied, one of the available pilots is reserved for the first Class A vessel in queue. The model also searches the number of available tugboats in the active direction and requests tugboats from the opposite side when it is less than 3. During the nighttime time windows, number of pilots at both sides is equalized to 6 and tugboats to 3 to meet the pilot and tugboat demand. Once a piloted vessel's passage in a certain direction is completed, the pilot is released from its current duty and included in the set of available resources for the opposite direction.

### 3.9. The Traffic Lanes and Overtaking

Vessels follow two main lanes, (the northbound or the southbound lanes) and the overtaking lane, if permitted, while transiting the Strait. The simulation model divides the whole Strait into 22 slices with stations. Slices are at eight cables (0.8 nautical miles ≈ 1.482 km.) intervals and in order to sustain a predetermined pursuit distance between vessels each slice is also composed of 2 cables long substations. The pilot embarking / disembarking stations are located at the 3. slice for southbound transit and at the 21. slice for northbound transit. Since stopping in the Strait for any reason is not allowed, vessels continuously move from one station to another during their stay in the Strait.

Overtaking is allowed in the Istanbul Strait except at the narrowest part, (between Kanlica and Vaniköy) according to speed differences among vessels (all vessels deciding to overtake are expected to seek the VTS permission).

The conditions for the overtaking process are as follows:

- When a vessel is in the overtaking lane, there should be no other vessel in this lane in the opposite direction at least up to the next station and the minimum distance between two adjacent vessels in the overtaking lane traveling in the same direction should at least be the pursuit distance.
- When a vessel x at a station observes vessel y overtaking another vessel z in front of it, vessel x looks if it can overtake vessel y. If vessel x cannot pass, just follows it; yet, if it can overtake, looks for the foremost vessel z. If it can catch up with vessel z, it overtakes both y and z. However, if it cannot pass z, decreases its speed and moves behind y and waits for another opportunity after the overtake of z by y is completed.
- After overtaking, vessels move back to the main lanes.

### 3.10. Visibility Conditions

Adverse meteorological conditions may cause the closure of the Strait to vessel traffic. One important meteorological event is the fog. According to the R&R:

- When visibility is less than one nautical mile in the Istanbul Strait, only one-way traffic is permitted. Moreover, dangerous cargo carrying vessels and vessels longer than 200 meters shall not enter to the Strait.

- When visibility in the Istanbul Strait is less than 0.5 mile, vessel traffic is suspended in both directions.

The visibility module in the simulation model reads the fog information from the visibility data of [2] externally. The data involved is comprised of start time, type (i.e. maximum visibility) and duration of each fog occurrence during the year. The fog initiations in the summer, fall and spring seasons are based on empirical distributions, while fog initiations in winter and fog durations in all seasons are assumed to come from phase type distribution [2].

The visibility module divides fog types into two, one allows just for one way traffic (called as FogType1) and the other stops all traffic (called as FogType2) and both cause increases in vessel waiting times. Before a vessel is allowed to enter the Strait from the active direction during daytime, visibility condition is checked; if there is a FogType2 event, the vessel waits until it disappears. After visibility conditions improve and traffic starts to flow again, the original schedule (including slack time assignment if any) is implemented as planned (i.e. traffic flow interruption caused by the fog just impacts the traffic flow planned in the fog duration). FogType1 does not affect daytime flows very much (since almost all vessel activity with the exception of class P vessel is uni-directional anyway); only the class P vessels coming from the opposite (passive) direction are stopped. When a FogType1 occur at nighttime, however, two-way traffic is suspended.

## 3.11. Current Conditions

Another major meteorological event in the Istanbul Strait which has a direct effect over vessel traffic and maritime risk is the currents. There are four types of current active on the Strait:

(i) The Southbound surface current: This is the most influential current. It is caused by the 40 cm altitude differences between the Black Sea and the Aegean Sea. This current type, is more intense in the middle of the Strait, loses its force towards Kandilli Bay and at southern parts. Its speed ranges in 6-7 knots.

(ii) The Northbound Undertow current: This current follows north from the Aegean Sea to the Black Sea. It is caused by the difference in density between the Black Sea and the Aegean Sea and is most influential at 45 meters depth.

(iii) Reverse currents (Eddies): This current is caused by geographical formations, bays and forelands. Sea water moving along these structures moves along the counter direction of the major current. Reverse currents may have influence on local traffic (whose routes are close to the shores), but have negligible influence on transit vessels.

(iv) Orkoz Currents: Due to strong southwest winds, the direction of the surface current sometimes reverses and speed of this reverse current may rise up to 6-7 knots. Orkoz currents may prohibit tankers and large vessels to enter the Istanbul Strait.

The current module of the simulation model is integrated to the model from the previous study [2]. In the study, the most effective southbound current is taken into account and a moving average function is built to estimate a daily base current value. Then, the current level at different regions of the Strait are assigned as predetermined percentages of the base value, based on historical current data [2].

Due to the current level in the Strait, some vessel classes (even all vessels with regard to current type) may not be admitted to the Strait according to the R&R which states that:

(i) When the main surface current exceeds four knots or when southern winds reverse the main current in the Istanbul Straits, all vessels carrying 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.

(ii) When the main surface current exceeds six knots or strong northerly currents and eddies are caused by southerly winds, all vessels carrying 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 [19].

In this study, current type described by the regulation (i) is denominated as current condition1 and current type described by the regulation (ii) is called as current condition2. Regarding the classification of vessels, Class A, B, C and E vessels having a speed less than 10 knots are not allowed to the Strait when there is current condition1 in the Strait, even if the other conditions are satisfied. All vessels in these classes have to wait in their queues when current condition2 arises (until current conditions stabilize).

# 4. VERIFICATION, VALIDATION AND OUTPUT ANALYSIS

This simulation model in this study is not exactly the same as the real traffic system in the Istanbul Strait, but rather a representation under some assumptions. Accordingly, the critical issue is to obtain consistent output values with the 2009 VTS data, regarding vessel entrance and transit activities, adverse meteorological conditions and pilot and tugboat services.

## 4.1. Assumptions of the Istanbul Strait Traffic Model

The conspicuous assumptions in the model are those simplifying the complex maritime traffic processes in the Istanbul Strait. One of them is about the interarrival time of vessels. Distributions of vessel interarrival times are assumed to be based on vessel types and their direction of flow. The effect of seasons over interarrival times is observed to be insignificant and therefore is omitted. The impact of meteorological conditions on the interarrival process is also ignored (with the exception of storm conditions in the Black Sea region slowing down transit activity).

Another key assumption is about the minimum pursuit distances among vessels. Considering regulations about vessel entrances (at least 8-cables-distance between consecutive vessels), it is presumed that the minimum time interval between two adjacent vessels while entering the Istanbul Strait is 14 minutes for northbound entrances and 12.5 minutes for southbound entrances in the base model, even though the VTS does not strictly follow a constant minimum pursuit distance. Accordingly, time interval between two adjacent Class A, Class B, Class C and D, E, P vessels is assumed to be 84, 56, 28, 14, 14 and 14 minutes respectively for northbound entrances and 75, 50 and 25, 12.5, 12.5 and 12.5 minutes respectively for southbound entrances.

Regarding pilotage services, it assumed that every day at the beginning of daytime traffic, all pilots attend at the agreed direction entrance and at the beginning of nighttime traffic, 6 pilots are left at the opposite direction in order not to obstruct opposite direction pilot requesting Class D vessels (who would otherwise be waiting for lack of pilots). Pilot availability controls are assumed to be made every hour. At every check, if the number of available pilots in the active direction is less than 6, they are supplied from the opposite direction. This is indeed a reasonable figure since even if every vessel entering the Strait in any entrance requests a pilot, the system needs 5 pilots in one hour of traffic flow and the remaining pilot is assumed as a safety requirement. Furthermore, the transit time of an off-duty pilot from one entrance to another is reckoned to be one hour.

Under these assumptions, the model is developed through the Arena 11.0 software, within the framework of a basic traffic scheduling model and submodels for vessel arrivals, external conditions like, fog and storm, ordinary vessel flow and the overtaking process. Although local traffic is out of the scope of this study, it is also represented in the model in order to at least visualize the Strait actual maritime structure. Next the model is examined for its correctness and validity.

### 4.2. Verification of the Simulation Model of the Maritime Traffic in the Istanbul Strait

After designing the model, it is critically important to make sure that it is correctly built. Although this seems like a simple observation, since the model is very complex, including long term simulation runs, multiple submodels, many inputs, variables and attributes, the interactions among these activities may not be easily caught. In the verification process,

- The logic of the model is carefully inspected.
- Codes and program modules are traced.
- Test runs are very helpful to check the model consistency.
- Animation property of the simulation software may easily track the flow of entities.
- Thereto, the model statistics are checked for their coherence.
- In addition to the model review by the model builder himself, another expert review would avoid bias and minimize oversights.

Due to the fact that the simulation model in this study consists of many submodels integrated to the main traffic model running concurrently, it is quite complicated to monitor the system. However some properties of the Arena 11.0 facilitate this operation. One of them is the trace module. It provides the user an opportunity to observe each entity event in the system and debug errors of logic. This module gives an output composed of time sequence of events, distinct label for each entity and system status change. With this module, arrival of each vessel, attributes assigned to it, its movement to the anchorage area or to the appropriate queues and its admittance to the Strait can be followed clearly, while simultaneously watching entities related to meteorological events affecting the system. Moreover, this feature may be stopped after some time or when a determined condition is satisfied to catch a specific event. In this study, this feature is often used for observing the system behavior after both entrances are closed due to the visibility problems (because of FogType2 events). This turned out to be one of the most time consuming details in developing the model since, as mentioned before, after the fog cleared, traffic should flow with the shifted schedule and this means that all related variables (the direction of traffic, duration of daytime or nighttime plan or even next day traffic starting time based on seasons) would have changed.

The other tool used for model verification is the animation feature of Arena. This is a very popular and persuasive characteristic of simulation programs. Animation reveals all events in the whole system; therefore, logic errors can be captured easily. Variable indicator of the Arena is also a frequently utilized tool in this study. The change in values of performance measures can directly be traced by variable indicators. The static screenshot of a typical animation for scene is shown in Figure 4.1.

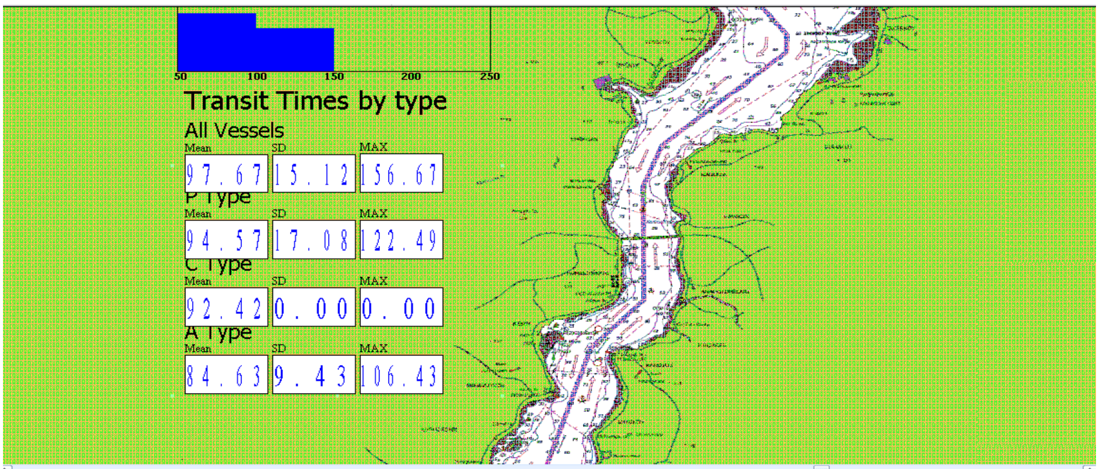


Figure 4.1. The animation of the model

As an additional confirmation activity, the whole logic in this model is compared with the previous model [15] and the overlooked details are added to the model.

### 4.3. Validation of the Simulation Model of the Maritime Traffic in the Istanbul Strait

It is expected that the values of the performance measures obtained from simulation runs match and display a similar behavior with the likely performance they would have had in real life. It is impossible to get identical results, yet considerably close outputs would be satisfying. In the validation process,

- Discrepancies between the predicted performance measures and observed data are tried to be figured out by using statistical techniques.
- It is contributive to compare the experimental results of the model with the corresponding previous model outputs.
- Events in the simulation model and in the real system are compared and checked whether they behave similarly.
- When extreme conditions are applied to input parameters, outputs should give plausible values.
- To utilize graphics for some performance measures through the simulation run provides a visual proof for model approval.

In this study, first, input validation is investigated. For example, the Arena Input Analyzer claims the best fitted distribution to northbound Class B to be LOGN (466, 1.32e+003) with square error 0.002301 (a considerably satisfying result); yet, p-values for the chi square and the K-G tests are both less than 0.05. When the model is run for validation, there are 300 fewer northbound B vessels created by the model, which is an unacceptable discrepancy for total of 1514 vessels. As another example, the best fitted distribution to northbound Class C is claimed to be -0001+ expo (118), with square error value 0.002301. P-values for the chi square and the K-G tests are both less than significance level and the number of northbound C vessels arriving at the Strait, in the validation run of the model is 4453, far away from the real data 4931. Therefore, it makes sense to make some modifications in distribution parameters; so, the average interarrival time for BN (350 minutes) and the average interarrival time for CN (106 minutes) are estimated from the 2009 data and the best distribution of interarrivals for BN is taken as 0.001+EXPO (350) and for CN is taken as -0.001 + EXPO (106). The simulation results and 2009 actual vessel arrivals are presented in Table 4.1, while all distribution functions for each vessel type are available in Appendix A.

Table 4.1. Comparison of the number of arrivals by vessel type

| Number of vessels | | | | |
|---|---|---|---|---|
| Vessel Type | Simulation | | 2009 Data | Relative Error (%) |
| | Average | Half Width | | |
| A_N | 1131.16 | 17.43 | 1156 | -2.14 |
| A_S | 1123.76 | 11.91 | 1105 | 1.69 |
| B_N | 1486.6 | 18.27 | 1514 | -1.8 |
| B_S | 1395.52 | 8.54 | 1430 | -2.41 |
| C_N | 4970.56 | 23.01 | 4931 | 0.8 |
| C_S | 5002.84 | 21.65 | 5023 | -0.4 |
| D_N | 16692.6 | 57.74 | 16739 | -0.27 |
| D_S | 16430.48 | 54.3 | 16431 | 0 |
| E_N | 831.52 | 9.78 | 841 | -1.12 |
| E_S | 920.76 | 14.1 | 937 | -1.73 |
| P_N | 625.48 | 12.55 | 659 | -5.08 |
| P_S | 622.28 | 13.09 | 656 | -5.14 |
| All | 51233.56 | | 51422 | -0.36 |

Based on both the half width and the relative error values, it is concluded that the generated number of vessel arrivals in a year is quite satisfying when compared to the 2009 data. Unfortunately, for some vessel classes, none of the interarrival probability distributions provides both low square errors and p- values less than 0.05. At this point, low square errors and visual fits with the help of histograms are presumed to be adequate.

Another technique deployed to verify the model is the extreme condition validation. All vessels arrival rates are increased by % 20 in a three month simulation run. Since the system should give logical responses to the unexpected situations, high values in average and maximum waiting time of vessels, number of vessels in queues, total number of vessels transiting the Istanbul Strait and pilot utilization levels realized as displayed in Table 4.2, make sense.

Table 4.2. Comparison of outputs in different rates

| Performance measures | Arrival rate | |
|---|---|---|
| | 20% higher | base |
| Average waiting time | 9272.75 | 541.20 |
| Maximum waiting time | 11739.63 | 735.26 |
| Number of vessels in queues | 1154.38 | 52.63 |
| Number of transited vessels | 14756.44 | 12845.78 |
| Pilot utilization | 0.25 | 0.23 |

Another approach to perceive the extreme conditions effect is reducing the total number of pilots in the model to 12 instead of 20. The model is run for one year with 25 replications and as expected, the pilot utilization, average, maximum waiting time of vessels and number of vessels in queues increased and total number of vessels passed the Strait decreased as indicated in Table 4.3 due to lack of pilot.

Table 4.3. Comparison of outputs regarding different number of pilots

| Performance measures | Number of pilots | |
|---|---|---|
| | 12 | 20 |
| Average waiting time | 3716.28 | 814.37 |
| Maximum waiting time | 4936.88 | 1894.11 |
| Number of vessels in queues | 385.28 | 79.94 |
| Number of transited vessels | 50511.72 | 51178.52 |
| Pilot utilization | 0.42 | 0.24 |

Comparison of model results and behavior with the results and behavior of previous studies is used as an additional validation tool. Especially the model in [15] facilitates to compare the results of performance measures and calibrate the decision variables when needed. Also with the help of the animation module, the critical performance measures are visible in any time during the model run and the abnormal results are noted to be adjusted.

The most conclusive of the validation methods in this study are the output comparisons with real 2009 data. The results of selected performance measures are sufficiently close to the data 2009 to support the claim that the model mimics the actual system reasonably well. Although some results are easily comparable (the average waiting time, transit time and total number of vessels passed over), density of vessels in the Strait, pilot utilization and number of vessels in queues results could not be measured.

### 4.4. Output Analysis for the Simulation Model

This model is run for the 13 months time period (between 1 December 2008 and 1 January 2010). The first month is assigned as the warm up period since it is not realistic to assume that there exists no vessels in queues nor in the anchorage area nor in the Strait at the actual simulation start time (1 January 2009).

The number of replications is a control parameter to achieve a reliable simulation model. Arena presents overall replications mean, half width of confidence interval (95%) with minimum and maximum values in the output report. As replications increase the half width decreases so confidence intervals of statistics get tighter. In this respect, the simulation model is replicated various times from 10 to 40 (Table 4.4) and average waiting time of vessels is observed. The descent in half width at 25 replications is decided to be adequate given the time constraint although further replications provide narrower confidence intervals.

Table 4.4. Change in half width under various replications

| Number of replications | Average waiting time | Half width |
|---|---|---|
| 10 | 846.48 | 274.36 |
| 15 | 830.79 | 193.75 |
| 20 | 831.35 | 153.66 |
| 25 | 814.37 | 123.13 |
| 30 | 811.70 | 107.00 |
| 35 | 790.70 | 93.25 |
| 40 | 774.50 | 83.18 |

### 4.4.1. The Output Analysis for the Base Scenario

The basic model supposes that vessel arrivals are distributed in line with the 2009 real data, while visibility, current and storm conditions are taken from the previous study [2] and imported to the model. There are 20 pilots and 6 tugboats in the system, as in the case of real maritime traffic system in the Istanbul Strait and the minimum time interval between two adjacent northbound vessels is accepted as 14 minutes and between two adjacent southbound vessels as 12.5 minutes (as discussed in section 4.1). The performance measures determined for the analysis are as follows:

- Average waiting time of vessels until entering to the Istanbul Strait;
- Average waiting time of AN until entering to the Istanbul Strait;
- Average waiting time of AS until entering to the Istanbul Strait;
- Average waiting time of BN until entering to the Istanbul Strait;
- Average waiting time of BS until entering to the Istanbul Strait;
- Average waiting time of CN until entering to the Istanbul Strait;
- Average waiting time of CS until entering to the Istanbul Strait;
- Average waiting time of DN until entering to the Istanbul Strait;
- Average waiting time of DS until entering to the Istanbul Strait;
- Average waiting time of EN until entering to the Istanbul Strait;
- Average waiting time of ES until entering to the Istanbul Strait;
- Average waiting time of PN until entering to the Istanbul Strait;
- Average waiting time of PS until entering to the Istanbul Strait;
- Maximum waiting time of vessels until entering to the Istanbul Strait;
- Total number of vessels passed the Istanbul Strait;
- Total number of northbound vessels passed the Istanbul Strait;
- Total number of southbound vessels passed the Istanbul Strait;
- Average transit time of vessels through the Istanbul Strait;
- Average number of vessels in queues;
- The entire Strait vessel density;
- Pilot utilization (weighed on time base).

The average waiting time of arriving (and ready) vessels until they are allowed into the Istanbul Strait is compared to the 2009 data in Table 4.5 and Figure 4.2. The overall waiting time is quite close to the real data, while, there are discrepancies among the average waiting times of vessel classes (in particular the major differences in comparison belong to smaller. The outstanding variation among critical classes A and B is due to the strictly rule based standardization in the simulation model of the number of A and B types scheduled to pass in stead of the frequent referral to subjective expert opininon in the real case.

Table 4.5. The average waiting time of vessels in the 2009 data and in the simulation runs of 25 replications

| Waiting Times (in minutes) | | | | |
|---|---|---|---|---|
| | | The Simulation Model | | |
| Vessel Type | 2009 Data | Average | Half Width | Relative Error (%) |
| A_N | 1397 | 1624.6 | 71.55 | 16.29 |
| A_S | 1660 | 1163.8 | 77.04 | -29.89 |
| B_N | 1187 | 1391.4 | 57.96 | 17.22 |
| B_S | 1430 | 1181.7 | 22.81 | -17.37 |
| C_N | 925 | 1055.2 | 59.34 | 14.08 |
| C_S | 761 | 1041.9 | 101.63 | 36.9 |
| D_N | 930 | 989.3 | 395.73 | 6.37 |
| D_S | 674 | 447 | 42.34 | -33.68 |
| E_N | 870 | 220.6 | 5.68 | -74.64 |
| E_S | 622 | 291.9 | 11.85 | -53.07 |
| P_N | 198 | 91.5 | 7.37 | -53.81 |
| P_S | 162 | 34.6 | 3.65 | -78.63 |
| All Vessels | 842 | 814.4 | 123.13 | -3.28 |

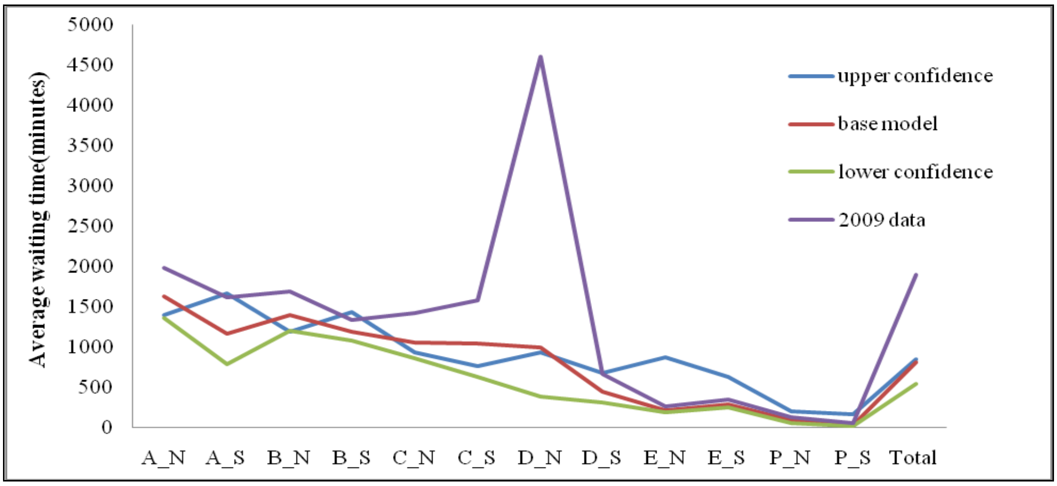


Figure 4.2. The comparison of average waiting time of vessels

The total number of vessels having transited the Strait of Istanbul in actual 2009 data and in the simulation model (base case) are displayed in Table 4.6. The proximity between the results is satisfactory. The main reason why the simulation model results regarding this performance measure are less than those in the real data is that the model produces fewer arriving vessels. The comparison for the number of each type of vessel passed from the Istanbul Strait is displayed in Figure 4.3 and they are also very close to one another.

Table 4.6. Total number of vessels passed the Istanbul Strait in the 2009 data and in the simulation runs of 25 replications

| | The 2009 Data | The Simulation Model | | | | Relative error (%) |
|---|---|---|---|---|---|---|
| Direction | Total | Mean | Half Width | Minimum average | Maximum average | |
| Total | 51412 | 51178 | 117.25 | 50649 | 51662 | -0.45 |
| Northbound | 25840 | 25870 | 75.95 | 25300 | 26038 | -0.44 |
| Southbound | 25572 | 25500 | 74.83 | 25120 | 25770 | -0.47 |

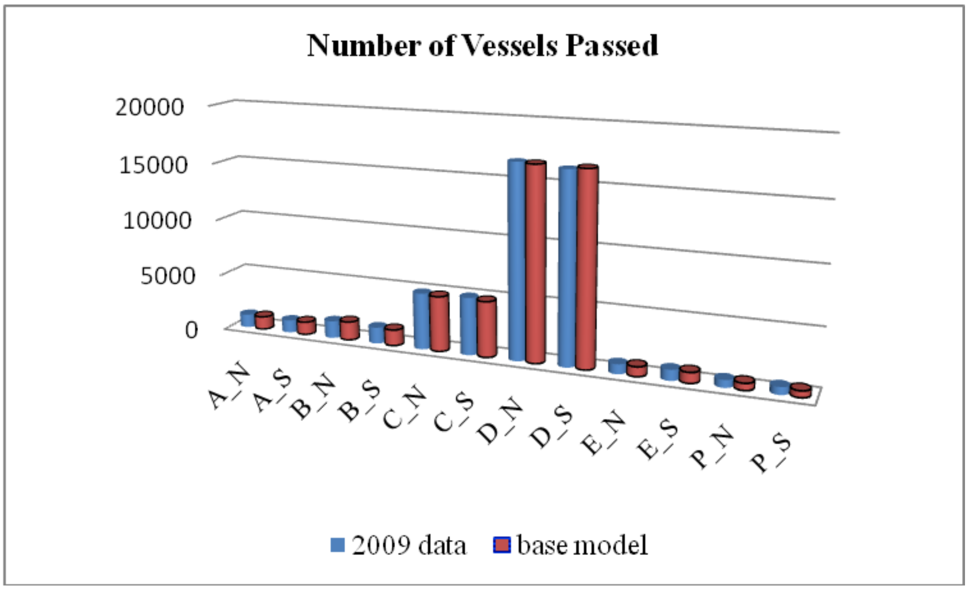


Figure 4.3. The average transit time of vessels according to their classes

The mean transit times of all vessels and of each class are displayed in Table 4.7. Although there is a slight difference between the simulation results and the real case, all relative error values are below 5 per cent and thus considered acceptable. One reason of the error variation may be badly fitted speed distributions generated from the 2009 VTS data.

Table 4.7. Average transit time of vessels through the Istanbul Strait in the 2009 data and in the simulation runs of 25 replications

| | The 2009 data | The Simulation Model | | | | |
|---|---|---|---|---|---|---|
| Class | Mean (min) | Mean (min) | Half Width | Minimum Average | Maximum Average | Error(%) |
| Total | 95.6 | 97.06 | 0.13 | 96.30 | 97.70 | -1.5 |
| A | 85.84 | 84.67 | 0.11 | 84.25 | 85.18 | 1.37 |
| B | 83 | 87.13 | 0.11 | 86.50 | 87.70 | -4.98 |
| C | 88.1 | 92.07 | 0.11 | 91.44 | 92.56 | -4.51 |
| D | 100.43 | 100.42 | 0.15 | 99.56 | 101.19 | 0.01 |
| E | 93.86 | 97.82 | 0.16 | 97.00 | 98.45 | -4.22 |
| P | 97.5 | 93.09 | 0.18 | 92.32 | 94.21 | 4.53 |

The attributes of vessels (length, stopover characteristics, pilot requests and anchorage durations) meteorological situations and scheduling policy influence the number of vessels in queues. Since the 2009 data does not include the queue information, the results could not be validated; however, when Figure 4.4, which presents the number of vessels in queues on the average is inspected, it is observed that the average number of southbound vessels waiting in queues is less than that of northbound vessels and this is comparative with the previous results of lesser waiting times associated with southbound vessels. It is also not surprising to observe the excessive length of Class D queues, while there are fewer vessels in Class A, B, E and P queues.

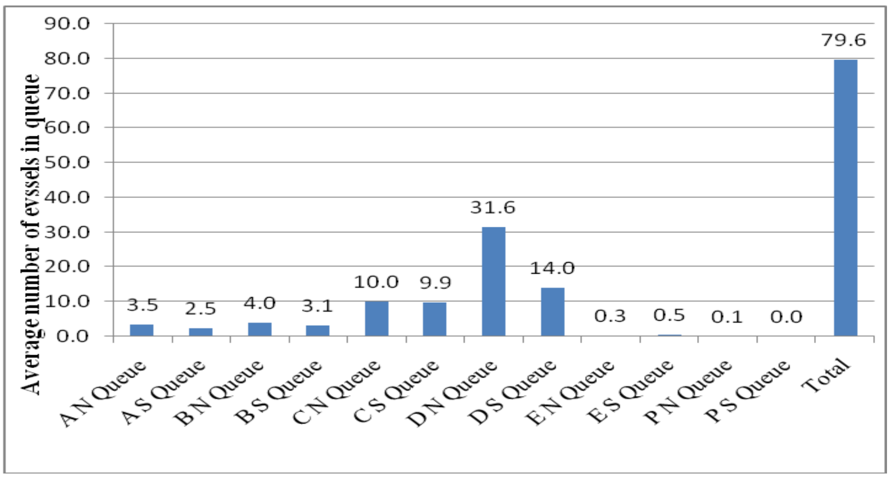


Figure 4.4. Average number of vessels in queues in the simulation runs of 25 replications

The average number of vessels transiting the Istanbul Strait at any time (the vessel density) obtained from 25 replications of the simulation model is displayed in Table 4.8. This performance measure also could not be confirmed because of lack of density information in the 2009 data, yet 9 vessels on the average sounds all right.

Table 4.8. The entire Strait vessel density in the simulation runs of 25 replications

| | Mean | Half width | Minimum average | Maximum average |
|---|---|---|---|---|
| Vessel Density in the Istanbul Strait | 9.45 | 0.03 | 9.3 | 9.59 |

The pilot and tugboat utilizations obtained from the simulation model with 25 replications are given in Table 4.9. The Arena software calculates the resource utilization by dividing the number of busy pilots or tugboats by the total number of available pilots and tugboats and estimates a time-weighted average. Again this output could not be confirmed, yet considering total number of pilots (20) and tugboats (6), the results are not surprising.

Table 4.9. Pilot and tugboat utilization in the simulation runs of 25 replications

| | The Simulation Model | | | |
|---|---|---|---|---|
| | Mean | Half width | Minimum average | Maximum average |
| Pilot utilization | 0.24 | 0 | 0.23 | 0.24 |
| Tugboat utilization | 0.01 | 0 | 0.09 | 0.01 |
| Number of busy pilots | 4.53 | 0.01 | 4.42 | 4.63 |
| Number of busy tugboats | 0.09 | 0 | 0.08 | 0.10 |

The base scenario results are persuasive when compared to the real data or checked against the previous studies and decision policies of the VTS experts. The average waiting time of vessels is the prime performance measure and is quite agreeable with the 2009 data. The total number of vessels that transited the Istanbul Strait in the simulation model is also very close to the actual 2009 data. The transit time of vessels has a slight difference with the real situation; however, it is explainable and independent of the scheduling algorithm. The pilot utilization result suggests that the implemented pilot assignment in this study is reasonable even though it could not be confirmed. The density of vessels in the Istanbul Strait also makes sense when the average value and the previous study results [2] are taken together.

### 4.4.2. The Output Analysis for Individual Scenarios

After the output analysis of the base model is accomplished, various individual scenarios are designed and again run with 25 replications and one month warm-up period. The aim of this part is to measure the sensitivity of the model against the changes in some parameters and give an opportunity to maritime experts to review their decision policies.

As mentioned before, the slack time enables more Class A vessels to enter the Strait and according to the algorithm, when this time period is larger than or equal to the minimum pursuit distance between two adjacent southbound class A vessels ($6*\mu$ ), the daytime traffic continues until the prevailing maximum daytime duration. The first such two of these scenarios investigate the effect of changing the slack time (one greatly increasing it, the other decreasing it). In the first extreme condition test, this time period criteria ($6*\mu$ ) is changed to $12*\mu$ and its effect, especially on the waiting time of vessels is investigated. The results (compared to the base scenario) displayed in Table 4.10 are not surprising. The average waiting times of northbound and southbound A vessels increase since the slack time length less than $12*\mu$ minutes refuses any Class A enter the Strait and start nighttime traffic. Accordingly, the waiting times of Class B vessels diminish because disuse of the slack time period with extra scheduled class A vessels facilitates earlier initiations of the nighttime traffic and thus more class B vessels enter the Strait. Moreover, average waiting times of class D vessels are also reduced, since nighttime traffic flow duration increases and bi-directional traffic allows simultaneous Class D transits from both directions.  The average waiting time of vessels are less than the base scenario result and the real situation in 2009, looking at the half width of the performance measure it is apparent that this scenario is not a good representation of the Istanbul Strait traffic system.

Table 4.10. The average waiting time of vessels when the slack time is 12* $\mu$

| Waiting Times (in minutes) | | | | | |
|---|---|---|---|---|---|
| Vessel Type | 2009 Data | Base Model | | Individual Model | |
| | | Average | Half Width | Average | Half Width |
| A_N | 1397 | 1624.6 | 71.55 | 2352.6 | 180.27 |
| A_S | 1660 | 1163.8 | 77.04 | 1819.3 | 156.83 |
| B_N | 1187 | 1391.4 | 57.96 | 1315.6 | 31.27 |
| B_S | 1430 | 1181.7 | 22.81 | 1107 | 18.98 |
| C_N | 925 | 1055.2 | 59.34 | 1064.2 | 54.4 |
| C_S | 761 | 1041.9 | 101.63 | 961.1 | 50.54 |
| D_N | 930 | 989.3 | 395.73 | 585.6 | 145.94 |
| D_S | 674 | 447 | 42.34 | 378.9 | 32.63 |
| E_N | 870 | 220.6 | 5.68 | 221.2 | 6.65 |
| E_S | 622 | 291.9 | 11.85 | 267.5 | 7.99 |
| P_N | 198 | 91.5 | 7.37 | 99.7 | 6.56 |
| P_S | 162 | 34.6 | 3.65 | 32.4 | 3.16 |
| All Vessels | 842 | 814.4 | 123.13 | 680.4 | 59.52 |

The results of the second extreme condition test where the slack time period is totally removed are shown in Table 4.11. Comparison of the realized waiting times with those in the base scenario show that, Class A average waiting time in this scenario is fairly less than the base scenario average, since the lack of slack time allows fewer A vessels into the Strait. As expected, the average waiting times of class B and D vessels decline, since more of such vessels may now transit in the “enlarged” nighttime windows. Other types of vessels are not considerably affected.

Table 4.11. The average waiting time of vessels when slack time is 0

| Waiting Times (in minutes) | | | | | |
|---|---|---|---|---|---|
| Vessel Type | 2009 Data | Base Model | | Individual Model | |
| | | Average | Half Width | Average | Half Width |
| A_N | 1397 | 1624.6 | 71.55 | 3275.5 | 401.2 |
| A_S | 1660 | 1163.8 | 77.04 | 2437.3 | 315.36 |
| B_N | 1187 | 1391.4 | 57.96 | 1295.1 | 30.06 |
| B_S | 1430 | 1181.7 | 22.81 | 1086.8 | 15.9 |
| C_N | 925 | 1055.2 | 59.34 | 1060.3 | 40.65 |
| C_S | 761 | 1041.9 | 101.63 | 940.8 | 38.66 |
| D_N | 930 | 989.3 | 395.73 | 555 | 147.1 |
| D_S | 674 | 447 | 42.34 | 362.3 | 29.08 |
| E_N | 870 | 220.6 | 5.68 | 224.1 | 6.9 |
| E_S | 622 | 291.9 | 11.85 | 264.9 | 7.67 |
| P_N | 198 | 91.5 | 7.37 | 112.1 | 7.3 |
| P_S | 162 | 34.6 | 3.65 | 27.2 | 2.7 |
| All Vessels | 842 | 814.4 | 123.13 | 695.8 | 62.21 |

For another investigation, the constant parametric pursuit distances among vessels are stochastically selected considering the fact that in reality the tracing distance is not exact and there are always deviations. In the first scenario, the minimum pursuit time interval between two adjacent northbound vessels is assumed to be uniformly distributed with lower and upper limits as 10 and 15 minutes respectively while the minimum pursuit time interval between two adjacent southbound vessels is assumed to be uniformly distributed with lower and upper limits as 9 and 14 minutes respectively. The results illustrated in Table 4.12 reveals that the alternative model increases the average waiting time of critical vessels, class A, B and even C when compared to the base scenario and substantially decreases the class D vessels average waiting time.

Table 4.12. The average waiting time of vessels when minimum pursuit time interval is uniformly distributed

| Waiting Times (in minutes) | | | | | |
|---|---|---|---|---|---|
| Vessel Type | 2009 Data | Base Model | | Individual Model | |
| | | Average | Half Width | Average | Half Width |
| A_N | 1397 | 1624.6 | 71.55 | 1829.50 | 95.08 |
| A_S | 1660 | 1163.8 | 77.04 | 1373.73 | 95.37 |
| B_N | 1187 | 1391.4 | 57.96 | 1729.65 | 57.14 |
| B_S | 1430 | 1181.7 | 22.81 | 1351.98 | 217.92 |
| C_N | 925 | 1055.2 | 59.34 | 1887.69 | 257.63 |
| C_S | 761 | 1041.9 | 101.63 | 2070.32 | 24.46 |
| D_N | 930 | 989.3 | 395.73 | 333.51 | 18.61 |
| D_S | 674 | 447 | 42.34 | 281.90 | 8.88 |
| E_N | 870 | 220.6 | 5.68 | 232.84 | 9.67 |
| E_S | 622 | 291.9 | 11.85 | 313.17 | 7.27 |
| P_N | 198 | 91.5 | 7.37 | 84.7694 | 2.67 |
| P_S | 162 | 34.6 | 3.65 | 29.3620 | 118.19 |
| All Vessels | 842 | 814.4 | 123.13 | 753.40 | 40.38 |

In other scenario, the minimum pursuit time interval between two adjacent northbound vessels is assumed to be exponentially distributed with mean 14 minutes, while the minimum pursuit time interval between two adjacent southbound vessels is assumed to be exponentially distributed with mean 12.5 minutes. As can be seen from Table 4.13, there is a noticeable increase in waiting times of Class B and Class C vessels, although the average waiting time is acceptable when compared to the real data. Furthermore, average waiting time of Class D vessels is far away from the real situation in 2009. The average number of vessels in queues is also investigated in this scenario (Figure 4.5) and is deduced that the number of Class B and C vessels in queues are higher but the number of Class D vessels are lower when compared to the base model. Remembering the priority of vessels, this scenario gives worse average waiting time results than the average values of the base scenario.

Table 4.13. The average waiting time of vessels when minimum pursuit time interval is exponentially distributed

| Waiting Times (in minutes) | | | | | |
|---|---|---|---|---|---|
| Vessel Type | 2009 Data | Base Model | | Individual Model | |
| | | Average | Half Width | Average | Half Width |
| A_N | 1397 | 1624.6 | 71.55 | 1522.6 | 51.9 |
| A_S | 1660 | 1163.8 | 77.04 | 1347.5 | 49.19 |
| B_N | 1187 | 1391.4 | 57.96 | 2160.7 | 99.27 |
| B_S | 1430 | 1181.7 | 22.81 | 1871.3 | 77.21 |
| C_N | 925 | 1055.2 | 59.34 | 2029.6 | 112.49 |
| C_S | 761 | 1041.9 | 101.63 | 2519.2 | 208.83 |
| D_N | 930 | 989.3 | 395.73 | 390 | 19.75 |
| D_S | 674 | 447 | 42.34 | 350 | 18.93 |
| E_N | 870 | 220.6 | 5.68 | 241.6 | 11.77 |
| E_S | 622 | 291.9 | 11.85 | 316.3 | 11.15 |
| P_N | 198 | 91.5 | 7.37 | 70.4 | 4.99 |
| P_S | 162 | 34.6 | 3.65 | 47.5 | 3.7 |
| All Vessels | 842 | 814.4 | 123.13 | 871 | 40.38 |

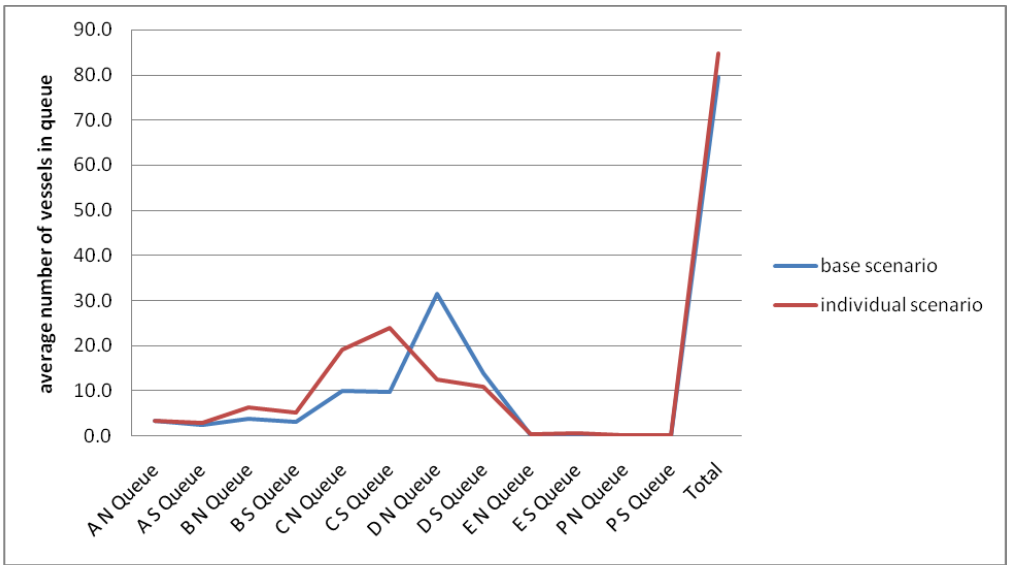


Figure 4.5. The average number of vessels in queues when minimum pursuit time interval is exponentially distributed

One other sensitivity analysis is performed in order to track the effect of minimum pursuit time intervals. In the first case, minimum pursuit time intervals of adjacent northbound and southbound vessels are altered as 12.5 and 11 minutes respectively. In the second case, minimum pursuit time intervals of adjacent northbound and southbound vessels are altered as 13.5 and 13.5 minutes respectively. In the last case, minimum pursuit time intervals of adjacent northbound and southbound vessels are altered as 14.5 and 13 minutes respectively. The results are compared in Table 5.15. As expected, in the first case, the average waiting time of vessels is the minimum due to shorter pursuit intervals and far away from the real situation. In the second case, the total average waiting times of vessels are very close to the 2009 average value and in the third case, the average waiting time of vessels is the maximum due to high pursuit intervals and values are considerably different from the real situation.

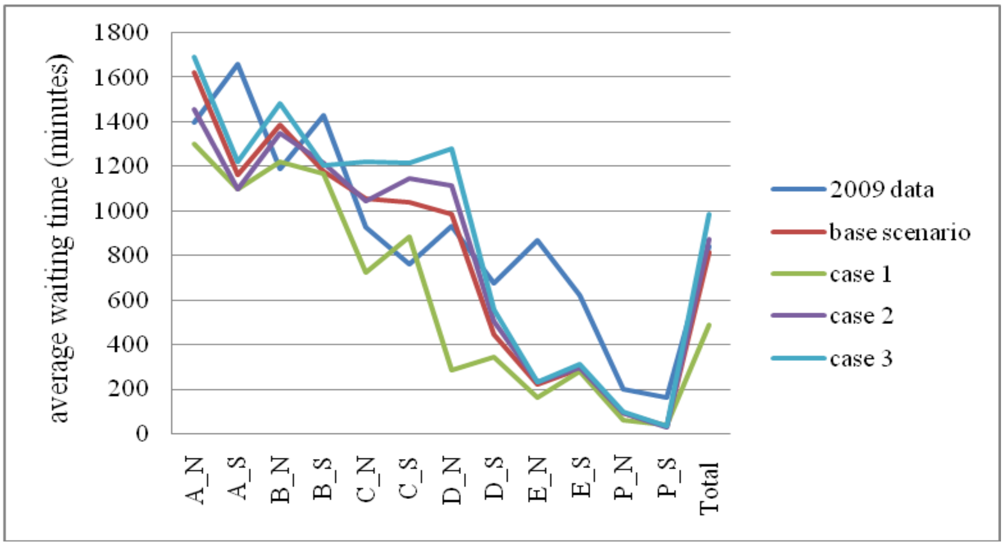


Figure 4.6. Average waiting time of vessels under various minimum pursuit time interval cases

In the last validation scenario, arrival rate of northbound and southbound Class A and B vessels are increased by 20 per cent. Unsurprisingly, the total average waiting times of vessels and in particular Class A and B and number of vessels in queues show a significant increases. This change in arrival rate cause increase in pilot utilization as well, since pilot demand of this two classes are almost one hundred per cent. The mentioned performance measures are displayed in Table 4.14.

Table 4.14. Outputs when Class A and B vessels arrival rate is increased by 20%

| Performance measures | 2009 Data | Base Model | Individual Model |
|---|---|---|---|
| | | Average | Average |
| Waiting time A_N | 1397 | 1624.6 | 5278.9 |
| Waiting time A_S | 1660 | 1163.8 | 4298.0 |
| Waiting time B_N | 1187 | 1391.4 | 2437.4 |
| Waiting time B_S | 1430 | 1181.7 | 1526.1 |
| Waiting time C_N | 925 | 1055.2 | 1029.5 |
| Waiting time C_S | 761 | 1041.9 | 1610.2 |
| Waiting time D_N | 930 | 989.3 | 753.3 |
| Waiting time D_S | 674 | 447.0 | 546.4 |
| Waiting time E_N | 870 | 220.6 | 237.4 |
| Waiting time E_S | 622 | 291.9 | 349.7 |
| Waiting time P_N | 198 | 91.5 | 116.3 |
| Waiting time P_S | 162 | 34.6 | 33.4 |
| Waiting time All | 842 | 814.0 | 1073.3 |
| Vessels in queues | unknown | 79.94 | 107.28 |
| Pilot utilization | unknown | 0.2368 | 0.2405 |

# 5. SCENARIO ANALYSIS AND RESULTS

In this chapter, various simulation experiments are carried out to observe the effects of the changes of one or more response variables (factors) on performance measures. Since these factor changes imply scenario analysis of the simulation model, the experiments measure the system performance in a more precise way.

## 5.1. Design of Simulation Experiments

Factorial designs are the most efficient experiment studies for two or more factors. In factorial design, all possible combinations of the treatments (levels) of factors in each replication of the experiment are investigated; therefore when interactions may be present, factorial design is essential in order to avoid misleading conclusions [18].

As further elaborated, in this section, 4 factors are selected for the scenario analysis of the simulation model:

- A: minimum pursuit distance between vessels (converted to time base);
- B: vessel profile;
- C: pilot policy;
- D: arrival rate.

### 5.1.1. The Factors and Levels

The levels of identified factors for scenario analysis are displayed in Table 5.1.

Table 5.1. Factors and their levels in the scenario analysis

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

The first factor with three levels is the minimum pursuit interval between two consecutive vessels. As discussed in Chapter 4, in the base scenario ( in high setting), there are at least 14 minutes between two northbound vessels at the Strait entrance, while it is 12.5 minutes for southbound vessels. At the average level (of pursuit distance), these intervals are decreased to 13.5 minutes for northbound vessels and 12 minutes for southbound vessels. At the low level (of pursuit distance), northbound vessels are sequenced to pass in at least 13.5 minutes intervals and southbound vessels in at least 11.5 minutes intervals.

Regarding the vessel profile factor, the low setting corresponds to the base scenario in which vessels demand pilots according to the pilot request frequency distribution of vessel subclasses generated from 2009 data. In the high setting, in addition to this random pilot demand, all vessels longer than 150 meters are routinely assigned a pilot while passing the Strait. A representation of the base scenario pilot frequency based on 2009 data and the high setting level pilot frequency is given in Table 5.2.

Table 5.2. Pilot request comparison in different levels

| | Pilot demand frequency (%) | |
|---|---|---|
| Vessel Classes | 2009 data | 2009 data+ vessels >=150m length |
| A | 99.86 | 100 |
| B | 96.64 | 100 |
| C | 73.45 | 85.35 |
| D | 32.83 | 32.83 |
| E | 38.36 | 38.36 |
| P | 74.98 | 76.12 |

Regarding the pilot availability factor, the number of available pilots is set at 16 for the low level and 20 for the average level (as is the case in the current system). As the highest level in this factor, 24 available pilots are assumed to be in the system.

According to the last factor, regarding the arrival rate of vessels, the low setting (which is the setting assumed in the base scenario) is taken as the rates estimated in the interarrival distribution for each subclass based on the 2009 data. In the average level, arrival rate of vessels is increased by 5 per cent (compared to the rates estimated based on the 2009 data) and in the high level, vessel arrival rates are increased by 10 per cent (compared to the rates estimated based on the 2009 data). (In other words, the parameters of the generated interarrival distributions are multiplied with 0.95 and 0.90 for the average and high levels of the arrival rate factor).

### 5.1.2. Output Performance Measures

In order to analyze the effects of the factors mentioned before, 13 response variables are selected from the Arena reports:

- Average total waiting time of vessels;
- Average total waiting time of class A vessels;
- Average total waiting time of class B vessels;
- Average total waiting time of class C vessels;
- Average total waiting time of class D vessels;
- Average total waiting time of class E vessels;
- Average total waiting time of class P vessels;
- Total number of vessels that have passed through the Strait;
- Total number of northbound vessels that have passed through the Strait;
- Total number of southbound vessels that have passed through the Strait;
- Average transit times of vessels that have completed their Strait transit;
- Pilot utilization of vessels in transit;
- Average vessel density in the Strait.

Accordingly, a total of 54 different scenarios (including the base scenario), are projected and run with 25 replications for a full factorial design. In other words, scenario analysis is composed of 1350 distinct observations. The outputs of these scenarios are gathered from Arena reports, the significant factors and their interactions are investigated through the ANOVA tables in the Design Expert 8.0 software.

ANOVA tables summarize how much of the variance in the data (total sum of squares) is accounted for by the factor effects (factor sum of squares) and how much is by random error (residual sum of squares). The model mean square estimates the model variance which is calculated by sum of squares (factor and residual sum of squares) divided by model degrees of freedom and the test statistic, f value is calculated for each term by model means square divided by error mean square to compare model variance with error (residual) variance. When this test statistic for any term is larger than the significance level ($\alpha$=0.05), null hypothesis which asserts that there is no factor effect is rejected and this term (factor or interaction) is added to the model.

One important assumption in analysis of variance is the homogeneous variance in the response variables assumption; yet, sometimes such a constant variance property is not satisfied. In this case, transformations are used to apply a mathematical function to the response data in order to improve the fit of the model to the data [18]. When the ratio of maximum response value to that of the minimum is larger than 10, this usually indicates a transformation is required. Transformations are also used for making residuals normally distributed with a constant variance. Design Expert 8.0 provides a broad range of possible transformations used in the analysis of several responses by the Box-Cox procedure.

While selecting the appropriate factors for the model, the R-squared statistic is checked. The term R-squared is the measure of the amount of variation around the mean explained by the analysis of variance model and it is desired to be close to one. However, this statistic always increases when a factor is added to the model even if the factor is statistically insignificant. The other statistic, the adjusted R-square is a measurement of the amount of variation around the mean explained by the model, adjusted for the number of terms in the model and decreases when the additional terms in the model are not statistically significant. In addition, Predicted R-squared is a measure of the amount of variation in new data determined by the model. It is desired that the predicted R-square and the adjusted R-squared values should be within 0.2 of each other; otherwise, it is concluded that there is a problem either stemming from the data or from the model. While selecting appropriate factors for the model, Design Expert warns about the hierarchical structure of the model. In other words, if an interaction is statistically significant to the model, then its main effects should also be included in the model even when they appear insignificant. Moreover, half normal probability plots are used to choose significant effects which are displayed in following subsections for each response variable. The outputs of 54 scenarios are displayed in Appendix B. The ANOVA tables and model graphs for significant main factors and factor interactions for all selected response variables of this study are also given in Appendix C.

## 5.2. Factors Affecting Response Variables

### 5.2.1. Average Waiting Time of Vessels

Inverse square transformation on the response values is applied through the Box-Cox procedure of the Design Expert in the analysis of average waiting times of vessels (in entering the Istanbul Strait) in order to stabilize response variance and to improve model fit. The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.1.

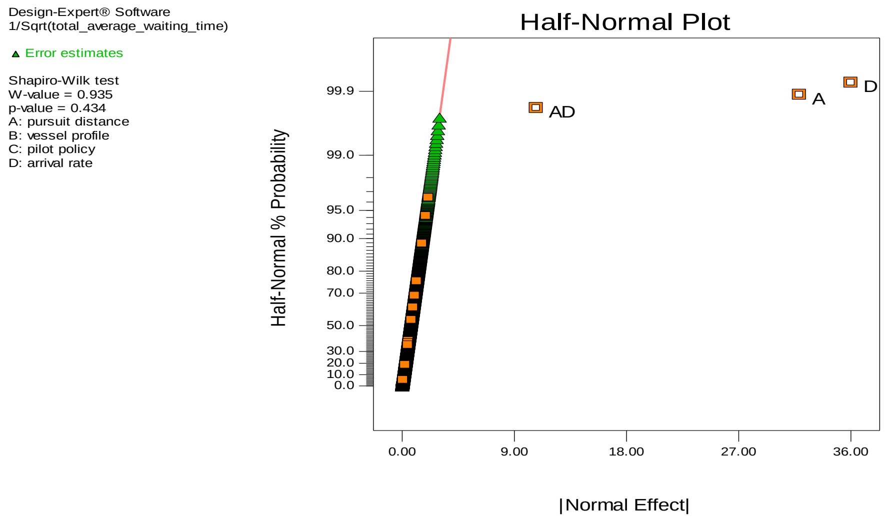


Figure 5.1. Half-normal probability plot for the effects of average waiting time of vessels

The significant factors affecting the average waiting time of vessels are determined by analyzing the related ANOVA table (Table C.1). According to this table, the Model F-value of 342.43 implies that the model is significant and there is only a 0.01 per cent chance that a "Model F-Value" this large could occur due to noise. "Prob>F values less than 0.05" indicate that the model terms are significant, while values greater than 0.1 indicate that the related model factors are not significant. In this regard, the main factors A, D and their interaction AD are identified as the most significant model terms. Since levels of individual factors are not the same, the Design Expert does not give per cent contribution information in the ANOVA output. Nevertheless, contribution of each significant factor calculated by means of mean square proportion is displayed in Table 5.3.

Table 5.3. Percent contribution of factors to average waiting time of vessels

| Factor | % Contribution |
|---|---|
| A | 38.23 |
| D | 59.28 |
| AD | 2.41 |

So, this preliminary output analysis indicates that, the most important factor regarding average waiting time of vessels is the arrival rate of vessels. As the arrival rate is increased, vessels have to wait longer in their queues until entrance is permitted. The second significant factor is the pursuit distance between vessels. As pursuit distance between two consecutive vessels (in entering the Strait) decreases, vessels wait less in queues. The interaction of arrival rate and pursuit distance is also effective for this response; that is, the maximum value for average waiting time occurs when arrival rate and pursuit distance are at their highest level.

For a detailed analysis, factors influencing average waiting time of each vessel class are investigated. The per cent contributions of these significant factors (displayed in Table 5.4) are compatible with the per cent contribution results shown in Table 5.3. Factors A, D and their interaction AD are the significant factors for average waiting time in each vessel class. Factor C is also effective on class E average waiting time.

Table 5.4. Percent contribution of factors to average waiting time of vessel classes

| | Vessel Class | | | | | |
|---|---|---|---|---|---|---|
| Factor | A | B | C | D | E | P |
| A | 14.29 | 25.37 | 26.64 | 38.98 | 33.32 | 45.31 |
| D | 81.13 | 68.72 | 39.02 | 57.87 | 64.71 | 53.08 |
| AD | 3.48 | 5.91 | 11.9 | 3.05 | 0.85 | 1.3 |
| C | | | | | 1 | |

The output analysis indicates that, the most important factor for average waiting time of each vessel class is the arrival rate of vessels. As the arrival rate is increased, due to high arriving vessel density, all types of vessels end up waiting longer in their queues. The second significant factor is the pursuit distance between vessels. As the pursuit distance between two consecutive class A, B, C, D, E and P vessels while entering to the Strait decrease, vessels end up waiting less in their queues. The interaction of arrival rate and pursuit distance is also effective in increasing or decreasing average waiting time of each vessel class, while the pilot policy is included as significant term for only class E vessels. When considering the contribution of these factors according to vessel types, it is apparent that per cent contribution of the pursuit distance factor regarding risky vessels A and B is less than that of smaller vessels D, E and P.

### 5.2.2. Total Number of Vessels Passed

The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.2.

The significant factors affecting the total number of vessels passed the Strait are determined by analyzing the related ANOVA table (Table C.8). According to this table, the Model F-value of 1704.32 implies that the model is significant and there is only a 0.01 per cent chance that a “Model F-Value” this large could occur due to noise. “Prob>F values less than 0.05” indicate that the model terms are significant, while values greater than 0.1 indicate that the related model terms are not significant. In this regard, all main factors A, B, C, D, their two way interactions AB, AC, AD, BC, BD, CD, three way interactions ABC, ABD, ACD, BCD and their four way interaction ABCD are significant model terms. Contribution of each significant factor calculated by means of the mean square proportion is displayed in Table 5.5.

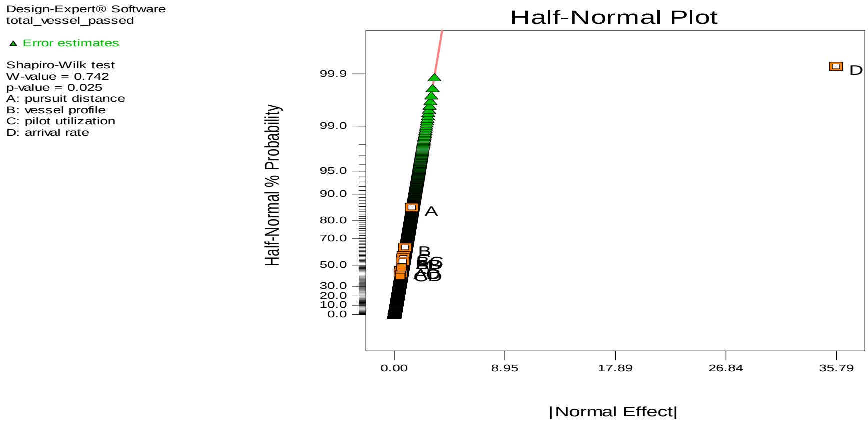


Figure 5.2. Half-normal probability plot for the effects of total number of vessels passed the Strait

Table 5.5. Percent contribution of factors to total number of vessels passed

| Factor | % Contribution |
|---|---|
| A | 0.30 |
| B | 0.13 |
| C | 0.13 |
| D | 98.14 |
| AB | 0.12 |
| AC | 0.12 |
| AD | 0.12 |
| BC | 0.12 |
| BD | 0.12 |
| CD | 0.11 |
| ABC | 0.12 |
| ABD | 0.12 |
| ACD | 0.13 |
| BCD | 0.12 |
| ABCD | 0.12 |

Related to the output analysis, the most important factor for the total number of vessels passed through the Istanbul Strait is the arrival rate of vessels. As the arrival rate is increased, number of vessels exiting the Strait increases. The second significant factor is the pursuit distance between vessels. As the pursuit distance decreases more vessels are able to enter the Strait in one year period. The third significant term is the pilot policy. As the number of available pilots increase, more vessels requesting pilot service are allowed to the Strait and this enables more vessel transit. The other significant main factor is the vessel profile. As vessels larger than 150 meters are assigned pilots during their transit, due to probable pilot shortage, fewer vessels are admitted to the Strait (more vessels end up waiting for pilot assignments). In this response, all two, three and four way interactions also add value to the model; however, except the arrival rate, all main factors and their interactions have little significance over this response.

### 5.2.3. Total Number of Northbound Vessels Passed

The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.3.

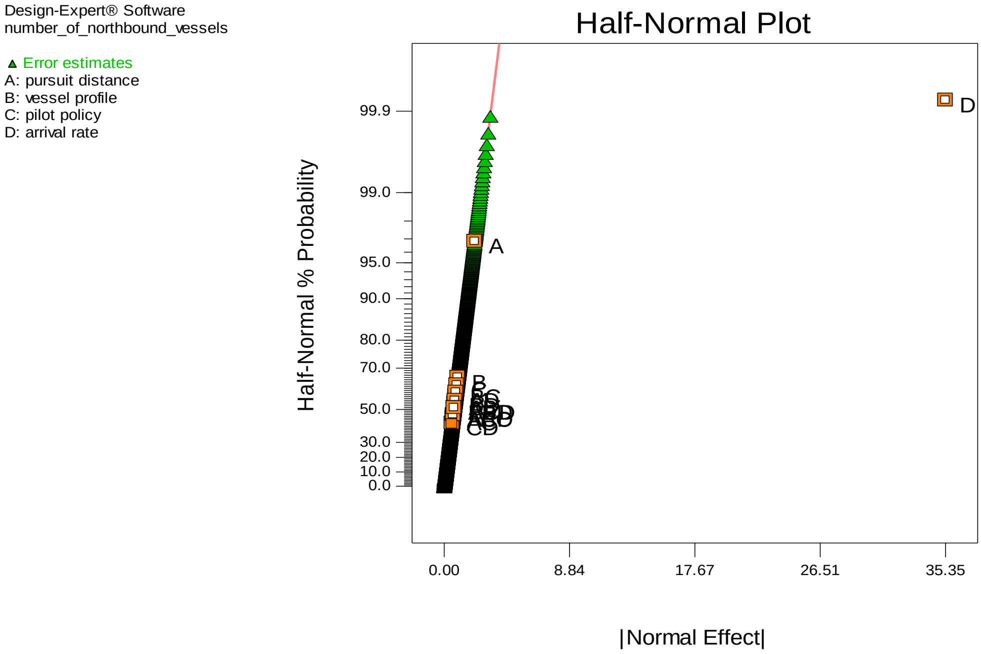


Figure 5.3. Half-normal probability plot for the effects of total number of northbound vessels passed the Strait

The significant factors affecting the total number of northbound vessels passed are determined by analyzing the related ANOVA table (Table C.9). According to this table, the Model F-value of 749.31 implies that the model is significant and there is only a 0.01 per cent chance that a "Model F-Value" this large could occur due to noise. "Prob>F values less than 0.05" indicate that the model terms are significant while values greater than 0.1 indicate the model terms are not significant. In this regard, all main factors A, B, C, D, their two way interactions AB, AC, AD, BC, BD, CD and three way interactions ABC, ABD, ACD, BCD are significant model terms. Contribution of each significant factor calculated by means of the mean square proportion is displayed in Table 5.6.

Table 5.6. Percent contribution of factors to total number of northbound vessels passed

| Factor | % Contribution |
|---|---|
| A | 0.54 |
| B | 0.14 |
| C | 0.15 |
| D | 97.87 |
| AB | 0.12 |
| AC | 0.12 |
| AD | 0.15 |
| BC | 0.14 |
| BD | 0.12 |
| CD | 0.11 |
| ABC | 0.12 |
| ABD | 0.13 |
| ACD | 0.14 |
| BCD | 0.13 |

Related to output analysis, the most important factor for the total number of northbound vessels passed through the Istanbul Strait is the arrival rate of vessels. As the arrival rate is increased, number of vessels exiting from the south end increases. The second significant factor is the pursuit distance between vessels. As the pursuit distance decreases more northbound vessels are able to enter the Strait in one year period. The third significant term is the pilot policy. As the number of available pilots increase, vessels requesting pilot service are allowed to the Strait and this enables more vessel transit. The other significant main factor is the vessel profile. As vessels larger than 150 meters are assigned pilots during their transit, due to probable pilot shortage, fewer vessels are admitted to pass the Strait. In this response, two and three way interactions are also significant terms for the model and as is the case in the previous response, except the arrival rate of vessels, all main factors and their interactions are of little importance.

### 5.2.4. Total Number of Southbound Vessels Passed

The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.4.

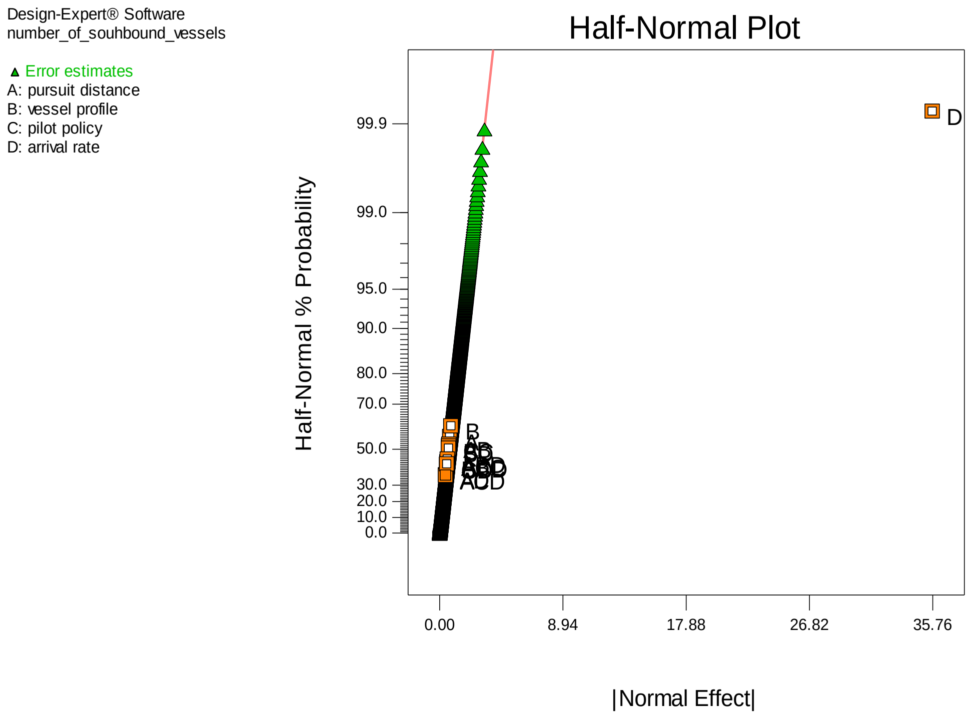


Figure 5.4. Half-normal probability plot for the effects of total number of southbound vessels passed the Strait

The significant factors affecting the average waiting time of southbound vessels are determined by analyzing the related ANOVA table (Table C.10). According to this table, the Model F-value of 1224.34 implies that the model is significant and there is only a 0.01 per cent chance that a "Model F-Value" this large could occur due to noise. "Prob>F values less than 0.05" indicate the model terms are significant while values greater than 0.1 indicate that the model terms are not significant. In this regard, all main factors A, B, C, D, their two way interactions AB, AC, AD, BC, BD, CD and three way interactions ABC, ABD, ACD, BCD are significant model terms. Contribution of each significant factor calculated by means of the mean square proportion is displayed in Table 5.7.

So, this preliminary output analysis indicates that similar to the previously analyzed performance measures, the most important factor regarding the total number of southbound vessels passed the Istanbul Strait is the arrival rate of vessels. The second significant factor is again the pursuit distance between vessels. In this response, two and three way interactions are also significant terms for the model yet again by far the most important factor is the arrival rate of vessels.

Table 5.7. Percent contribution of factors to total number of southbound vessels passed

| Factor | % Contribution |
|---|---|
| A | 0.13 |
| B | 0.11 |
| C | 0.11 |
| D | 98.54 |
| AB | 0.11 |
| AC | 0.11 |
| AD | 0.10 |
| BC | 0.11 |
| BD | 0.11 |
| CD | 0.11 |
| ABC | 0.11 |
| ABD | 0.12 |
| ACD | 0.12 |
| BCD | 0.11 |

### 5.2.5. Pilot Utilization

The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.5.

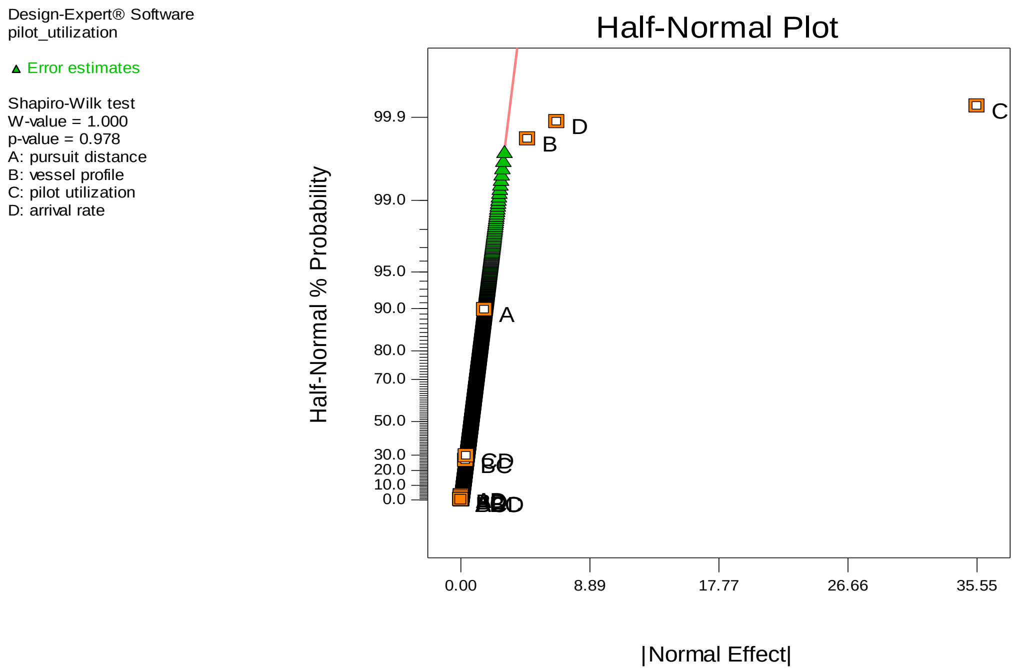


Figure 5.5. Half-normal probability plot for the effects of vessel pilot utilization

The significant factors affecting the pilot utilization of vessels are determined by analyzing the related ANOVA table (Table C.11). According to this table, the Model F-value of 99166.78 implies that the model is significant. "Prob>F values less than 0.05" indicate that the model terms are significant. In this regard, all main factors A, B, C, D, their two way interactions AB, AC, AD, BC, BD, CD and three way interactions ABC and BCD are identified as the significant model terms. Contribution of each significant factor calculated by means of the mean square proportion is displayed in Table 5.8.

Table 5.8. Percent contribution of factors to vessel pilot utilization

| Factor | % Contribution |
|---|---|
| A | 0.33 |
| B | 3.09 |
| C | 92.9 |
| D | 3.5 |

The output analysis indicates that, the most important factor regarding pilot utilization is the pilot policy. As the number of available pilots in the system increases, pilot utilization decreases. The second significant factor is the arrival rate of vessels. As the number of arriving vessels increases, more pilots are required, so pilot utilization increases too. The third significant term is the vessel profile. As pilots are automatically assigned to all vessels larger than 150 meters during their transit, pilot demand increases, correspondingly pilot utilization increases, as well. The last main effective factor is the pursuit distance between vessels. As vessels enter the Strait more frequently, the pilot utilization increases. Although contributions are very low, in this response two and three way interactions are also significant terms for the model.

### 5.2.6. Average Vessel Density

The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.6.

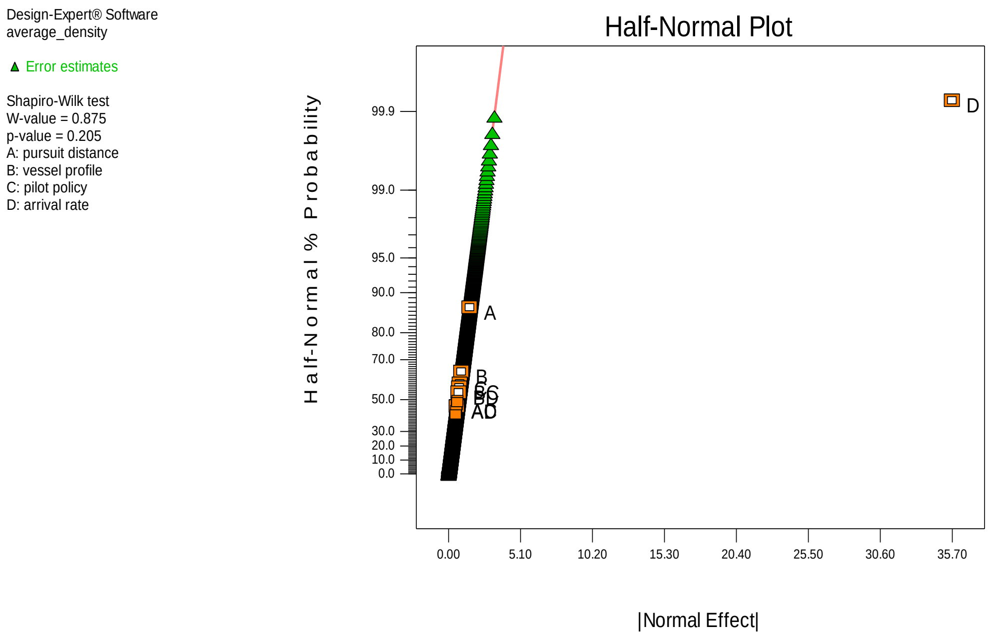


Figure 5.6. Half-normal probability plot for the effects of vessel density

The significant factors affecting the vessel density in the Strait is determined by analyzing the related ANOVA table (Table C.12). According to this table, the Model F-value of 1478.50 implies that the model is significant. "Prob>F values less than 0.05" indicate that the model terms are significant. In this regard, all main factors A, B, C, D and their two way interactions AB, AC, AD, BC, BD, CD are identified as the significant model terms. Contribution of each significant factor calculated by means of the mean square proportion is displayed in Table 5.9.

Table 5.9. Percent contribution of factors to vessel density

| Factor | % Contribution |
|---|---|
| A | 0.31 |
| B | 0.13 |
| C | 0.14 |
| D | 98.57 |
| AB | 0.12 |
| AC | 0.12 |
| AD | 0.12 |
| BC | 0.13 |
| BD | 0.12 |
| CD | 0.11 |

The preliminary output analysis indicates that the most important factor regarding vessel density is the arrival rate of vessels. As the arrival rate increases, vessel density per unit time increases. Furthermore, the pursuit distance is also effective on the vessel density. A lower level pursuit distance gives vessels better opportunity for overtaking and thus decreases transit times, while increasing the number of vessels per unit time. Pilot policy factor has little but significant effect over this response. Higher levels of pilot availability leads to fewer vessels waiting for pilot assignments thus to having more “ready” vessel just waiting to fill the Strait entrance time slots; thus higher vessel density levels are attained. Vessel profile has also little but meaningful effect over the vessel density. Vessels longer than 150 meters are required to take pilots and a probable pilot unavailability keeps such vessels waiting thus decreasing the vessel density. Although contributions are considerably low, in this response two way interactions are also significant terms for the model.

### 5.2.7. Average Vessel Transit Time

The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.7.

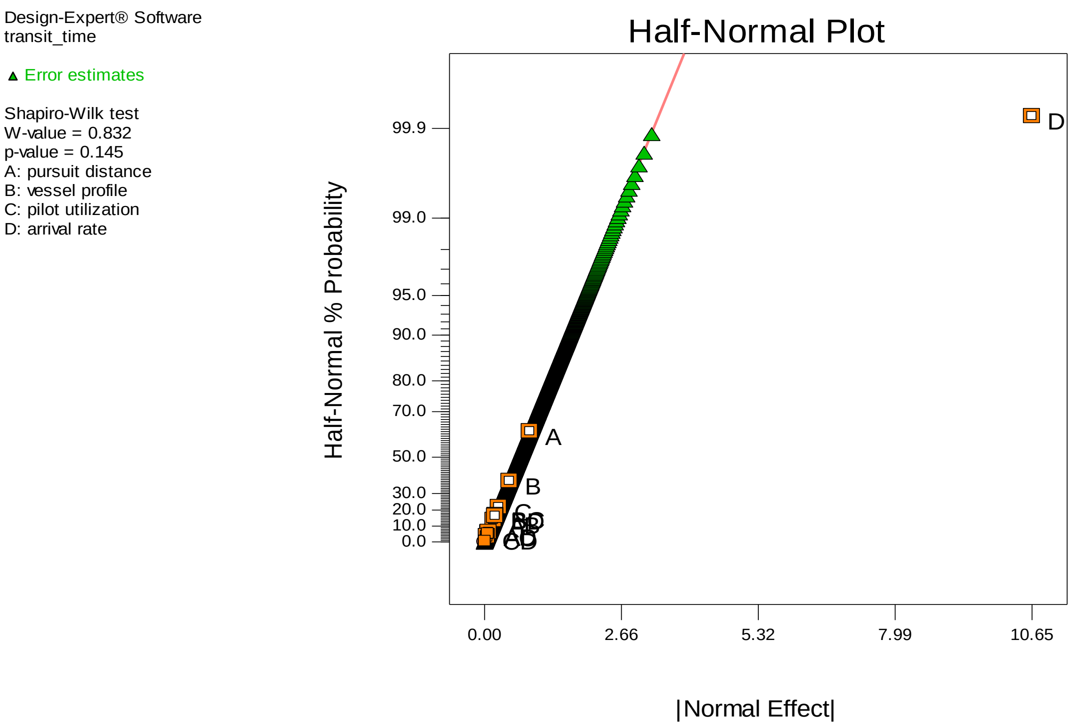


Figure 5.7. Half-normal probability plot for the effects of vessel transit time

The significant factors affecting the vessel transit time in the Strait is determined by analyzing the related ANOVA table (Table C.13). According to this table, the Model F-value of 4.98 implies that the model is significant. “Prob>F values less than 0.05” indicate that the model factors are significant. In this regard, only factor D is the significant model term. Contribution of this significant factor calculated by means of the mean square proportion is displayed in Table 5.10.

Table 5.10. Percent contribution of factors to the vessel transit time

| Factor | % Contribution |
|---|---|
| D | 88.55 |

The only significant factor for the average vessel transit time is the arrival rate. This factor indirectly increases transit duration through causing higher vessel density in the Strait. As vessel density increases, vessels less frequently overtake each other and high speed vessels are obliged to transit behind low speed ones causing longer transit times.

## 5.3. Factors Affecting the Response Variables under High Arrival Rate Conditions

In this section, 4 factors influencing the response variables under high arrival rate conditions (number of arrived vessels increased by 10 per cent) are analyzed. These factors with determined levels are given in Table 5.11.

Table 5.11. Factors and their levels in the varied scenario analysis

| Factor | Name | Low | Average | High |
|---|---|---|---|---|
| A | pursuit time | 13.5N-12S | | 14N-12.5S |
| B | vessel profile | base | | >=150 m |
| C | pilot policy | 16 | 20 | 24 |
| D | Visibility | base | | low |

Factors A, B and C have impacts similar to those investigated and reported in the previous section. Regarding the visibility factor (D), the low setting describes the base scenario in which vessels encounter fog events according to the visibility submodel discussed in Section 3.10, whereas in the high setting, the fog pattern of the worst case (i.e. the autumn fog realizations which have the longest fog durations) is chosen as the visibility data for the whole year. The durations of FogType2 of each season in the low setting (base scenario) is displayed in Table 5.12.

Table 5.12. Fog durations in each season

| Season | FogType2 duration(min) |
|---|---|
| winter | 1679 |
| spring | 1990 |
| summer | 310 |
| autumn | 4406 |

In the full factorial analysis of the related scenarios, the 24 different scenarios are experimented through 25 replications (i.e. the scenario analysis is composed of 600 distinct observations). The outputs of the scenarios gathered from the Arena reports are displayed in Appendix D, the significant factors and their interactions are identified through the ANOVA tables in the Design Expert 8.0 software.

### 5.3.1. Average Waiting Time of Vessels under High Arrival Rate Conditions

Natural log transformation on the response values is applied through the Box-Cox procedure of the Design Expert in the analysis of the average waiting times of vessels (in entering the Istanbul Strait), in order to stabilize response variance and to improve model fit. The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.8.

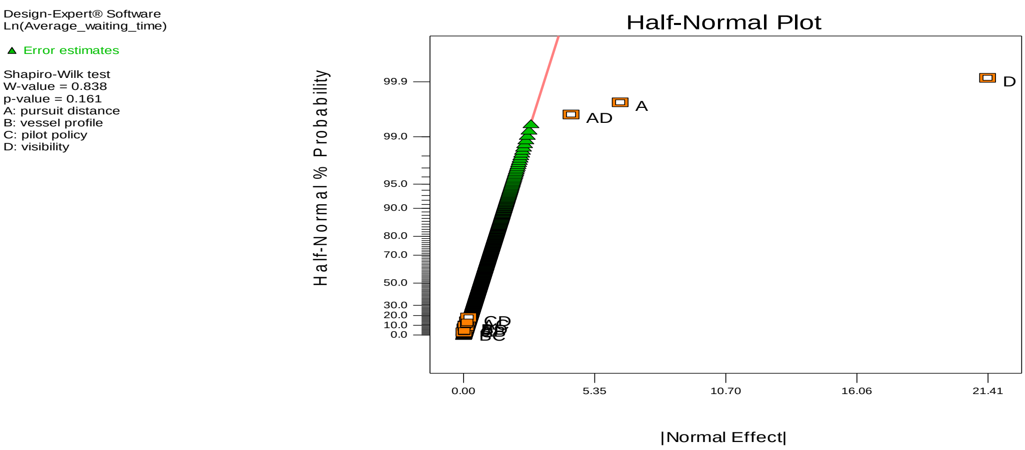


Figure 5.8. Half-normal probability plot for the effects of average waiting time of vessels under high arrival rate

The significant factors affecting the average waiting time of vessels under high arrival rate are determined by analyzing the related ANOVA table (Table D.1). According to this table, the Model F-value of 237.95 implies that the model is significant. "Prob>F values less than 0.05" indicate that the model terms are significant. In this regard, the main factors A, D and their interaction AD are significant model terms. Contribution of each significant factor calculated by means of the mean square proportion is displayed in Table 5.13.

Table 5.13. Contribution of factors to average waiting time under high arrival rate

| Factor | % Contribution |
|---|---|
| A | 7.92 |
| D | 88.22 |
| AD | 3.74 |

So this preliminary output analysis indicates that the most important factor regarding average waiting time of vessels is the visibility. When visibility is at high level (i.e. poor visibility conditions), vessels end up waiting longer in their queues. The second significant factor is the pursuit distance between vessels. As the pursuit distance between two consecutive vessels decreases, vessels end up waiting less in their queues. The interaction of visibility and pursuit distance is also effective in this response that is, the maximum value for average waiting time occurs when visibility and pursuit distance are at their high settings.

The average waiting times of each class with what four factors are also analyzed and the significant factors are displayed in Table 5.14, whereas the related ANOVA tables and graphs are illustrated in Appendix D.

Table 5.14. Significant factors for each vessel class average waiting time under high arrival rate

| | Vessel Class | | | | | |
|---|---|---|---|---|---|---|
| Factor | A | B | C | D | E | P |
| A | 8.93 | 11.70 | 18.95 | 12.35 | 6.11 | 1.65 |
| D | 84.80 | 78.54 | 63.70 | 77.44 | 92.81 | 98.28 |
| AD | 6.10 | 9.44 | 17.30 | 10.10 | 0.84 | |

### 5.3.2. Total Number of Vessels Passed under High Arrival Rate Conditions

The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.9.

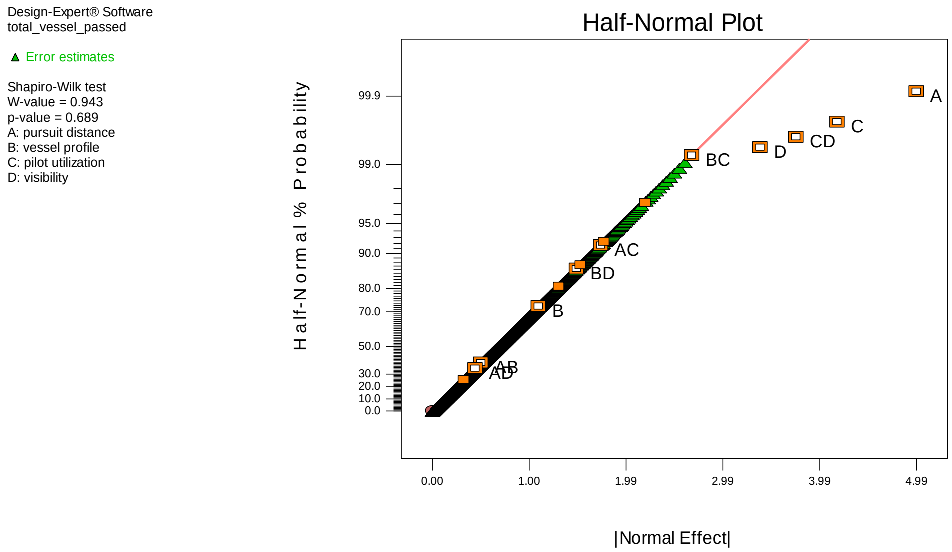


Figure 5.9. Half-normal probability plot for the effects of total number of vessels passed the Strait under high arrival rate

The significant factors affecting the number of vessels are passed the Strait determined by analyzing the related ANOVA table (Table D.2). According to this table, the Model F-value of 1311142 implies that the model is significant. “Prob>F values less than 0.05” indicate that the model terms are significant. In this regard, the main factors A, C, D and two way interactions BC and CD are significant model terms. Contribution of each significant factor calculated by means of the mean square proportion is displayed in Table 5.15.

Table 5.15. Percent contribution of factors to total number of vessels passed under high arrival rate

| Factor | % Contribution |
|---|---|
| A | 36.80 |
| C | 15.40 |
| D | 16.89 |
| BC | 7.24 |
| CD | 12.78 |

According to the output analysis, the most important factor for total number of vessels passed through the Strait is the pursuit distance between vessels. At high pursuit distances fewer vessels are able to enter the Strait in one year period. The second significant term is the visibility conditions. In low visibility conditions, vessels end up waiting longer in queues so, fewer vessels pass the Strait. The third efficient factor is the pilot availability. At high settings of pilot availability, more vessels requesting pilot are able to transit without delay. In this response, interaction of B and C factors and interaction of C and D are also significant for the model.

### 5.3.3. Total Number of Northbound Vessels Passed under High Arrival Rate Conditions

The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.10.

The significant factors affecting the average waiting time of vessels are determined by analyzing the related ANOVA table (Table D.3). According to this table, the Model F-value of 933468.4 implies that the model is significant. “Prob>F values less than 0.05” indicate that the model terms are significant. In this regard, the main factors A, D and their two way interaction AD are significant model terms. Contribution of each significant factor calculated by means of the mean square proportion is displayed in Table 5.16.

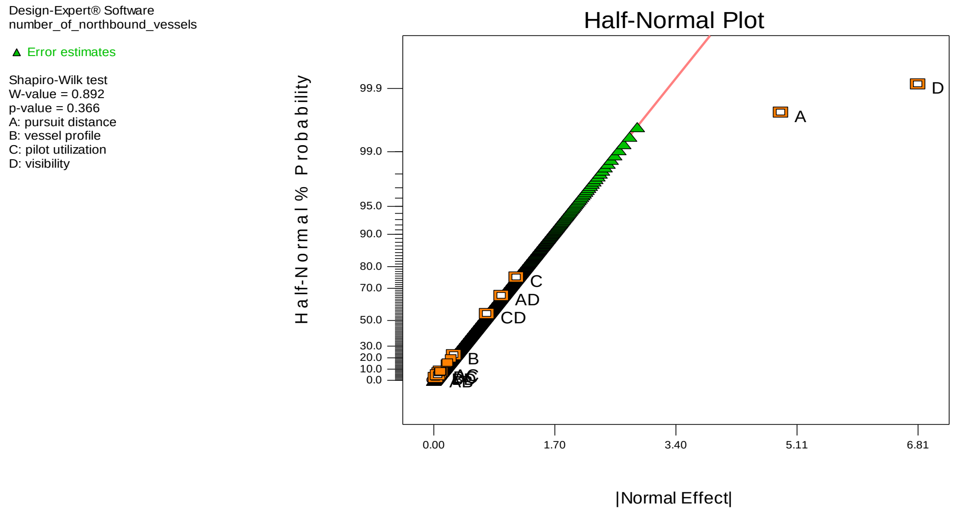


Figure 5.10. Half-normal probability plot for the effects of total number of northbound vessels passed the Strait under high arrival rate

Table 5.16. Percent contribution of factors to total number of northbound vessels passed under high arrival rate

| Factor | % Contribution |
|---|---|
| A | 31.96 |
| D | 62.21 |
| AD | 1.22 |

The output analysis indicates that the most important factor for total number of northbound vessels passed through the Strait when vessel arrival rate is increased by 10 per cent is the visibility conditions. The second significant factor is the pursuit distance between vessels. Interaction of pursuit distance and visibility factors has also important effect such that low level of both factors increases this response value.

### 5.3.4. Total Number of Southbound Vessels Passed under High Arrival Rate Conditions

The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.11.

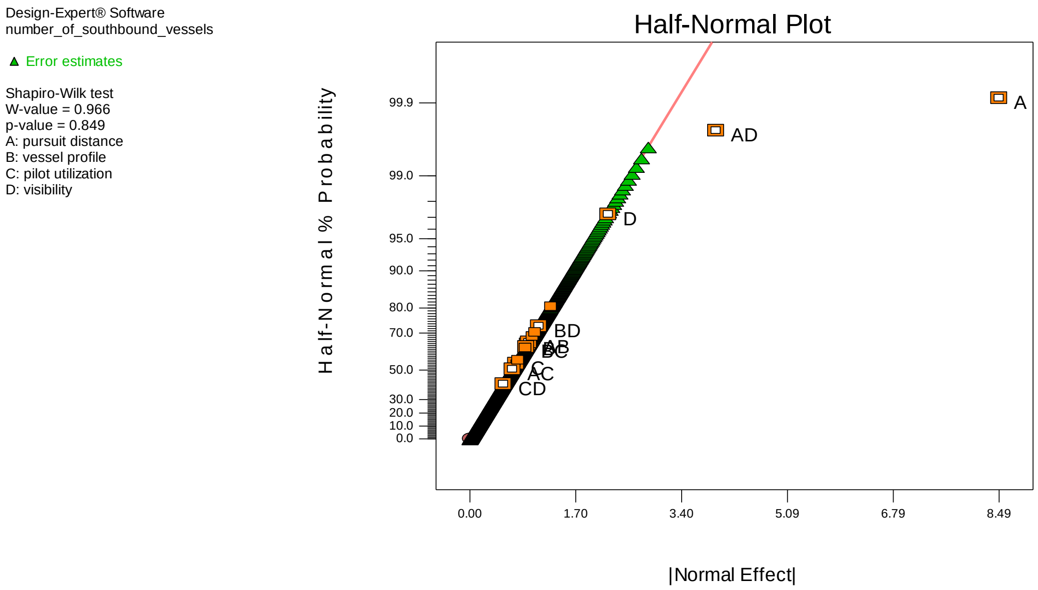


Figure 5.11. Half-normal probability plot for the effects of total number of southbound vessels passed the Strait under high arrival rate

The significant factors affecting the average waiting time of southbound vessels are determined by analyzing the related ANOVA table (Table D.4). According to this table, the Model F-value of 215837.1 implies that the model is significant. “Prob>F values less than 0.05” indicate that the model terms are significant. In this regard, the main factors A, D and their two way interaction AD are significant model terms. Contribution of each significant factor calculated by means of the mean square proportion is displayed in Table 5.17.

Table 5.17. Percent contribution of factors to total number of southbound vessels passed under high arrival rate

| Factor | % Contribution |
|---|---|
| A | 72.37 |
| D | 4.95 |
| AD | 15.65 |

The output analysis indicates that the most important factor for total number of southbound vessels passed through the Istanbul Strait when vessel arrival rate is increased by 10 per cent is the visibility conditions. The second significant factor is the pursuit distance between vessels. Interaction of pursuit distance and visibility factors has also important effect such that low levels of both factors increase the response value.

### 5.3.5. Pilot Utilization under High Arrival Rate Conditions

The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.12.

The significant factors affecting the pilot utilization of vessels are determined by analyzing the related ANOVA table (Table D.5). According to this table, the Model F-value of 120422.6 implies that the model is significant. “Prob>F values less than 0.05” indicate that the model terms are significant. In this regard, all main factors A, B, C, D are significant model terms. Contribution of each significant factor calculated by means of the mean square proportion is displayed in Table 5.18.

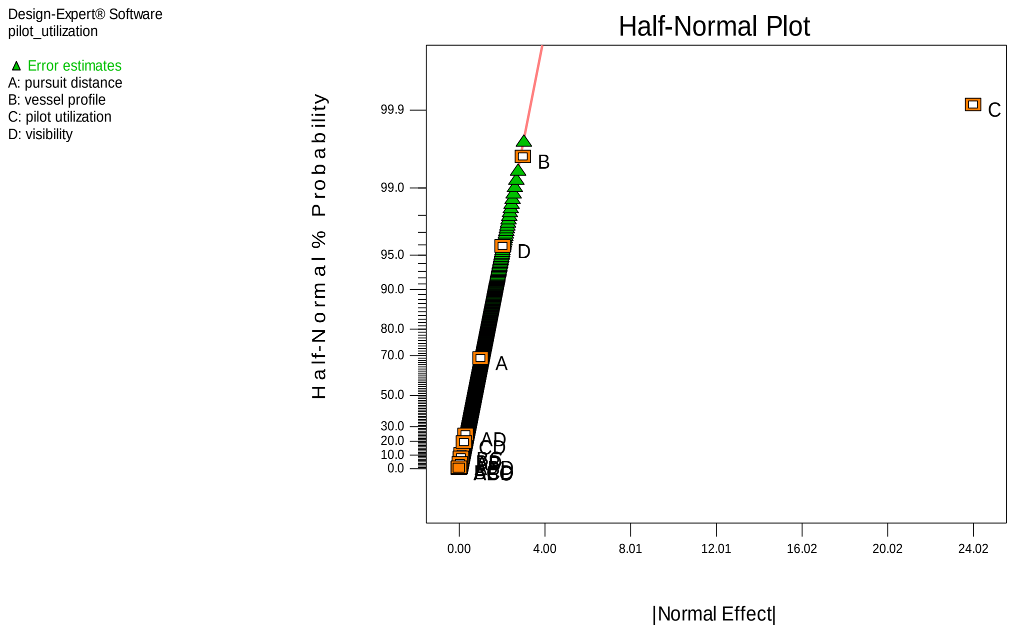


Figure 5.12. Half-normal probability plot for the effects of vessel pilot utilization under high arrival rate

Table 5.18. Percent contribution of factors to vessel pilot utilization under high arrival rate

| Factor | % Contribution |
|---|---|
| A | 0.34 |
| B | 2.92 |
| C | 95.23 |
| D | 1.37 |

Related to the output analysis, the most important factor for pilot utilization when vessel arrival rate is increased by 10 per cent is the pilot policy. As number of available pilots in the system increases, pilot utilization decreases. The second significant term is the vessel profile. The third significant factor is visibility conditions. The last main effective factor is the pursuit distance between vessels.

### 5.3.6. Average Vessel Density under High Arrival Rate Conditions

The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.13.

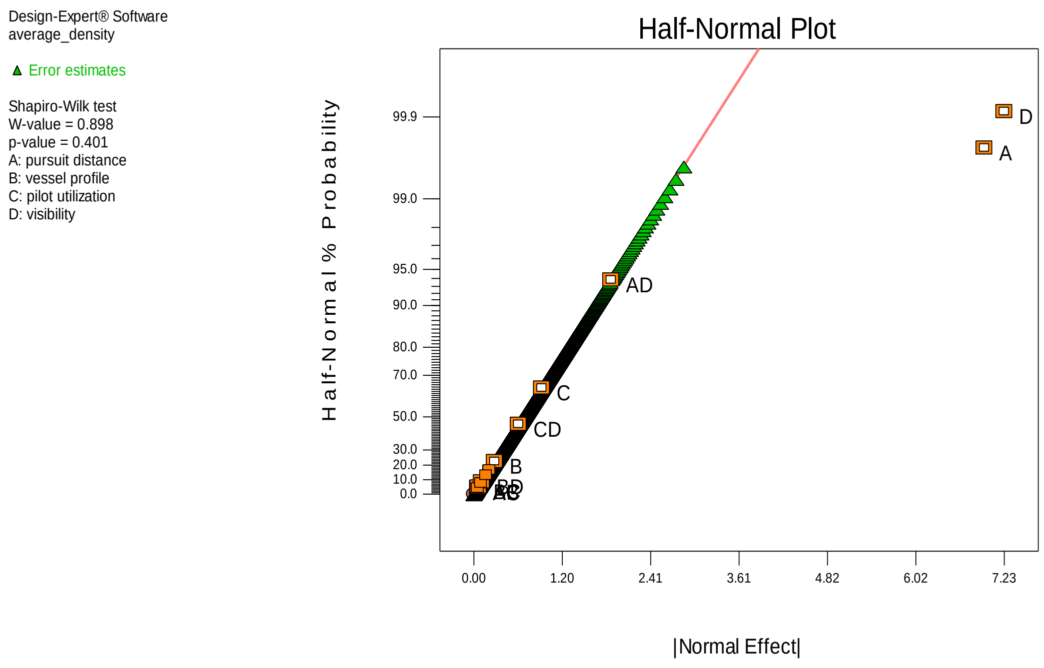


Figure 5.13. Half-normal probability plot for the effects of vessel density under high arrival rate

The significant factors affecting the vessel density in the Strait is determined by analyzing the related ANOVA table (Table D.6). According to this table, the Model F-value of 7.69 implies that the model is significant. "Prob>F values less than 0.05" indicate that the model terms are significant. In this regard, two main factors A and D and their two way interaction AD are significant model terms. Contribution of each significant factor calculated by means of mean square proportion is displayed in Table 5.19.

Table 5.19. Percent contribution of factors to vessel density under high arrival rate

| Factor | % Contribution |
|---|---|
| A | 45.24 |
| D | 48.83 |

Related to the output analysis, again the most important factor for vessel density is the visibility conditions. Furthermore, pursuit distance is effective on the vessel density. Lower pursuit distances increase opportunities for vessels the overtaking and decrease transit time, thus the number of vessels per unit time increases.

### 5.3.7. Average Transit Time of Vessels under High Arrival Rate Conditions

The half-normal probability plot of normal effects of the significant factors is displayed in Figure 5.14.

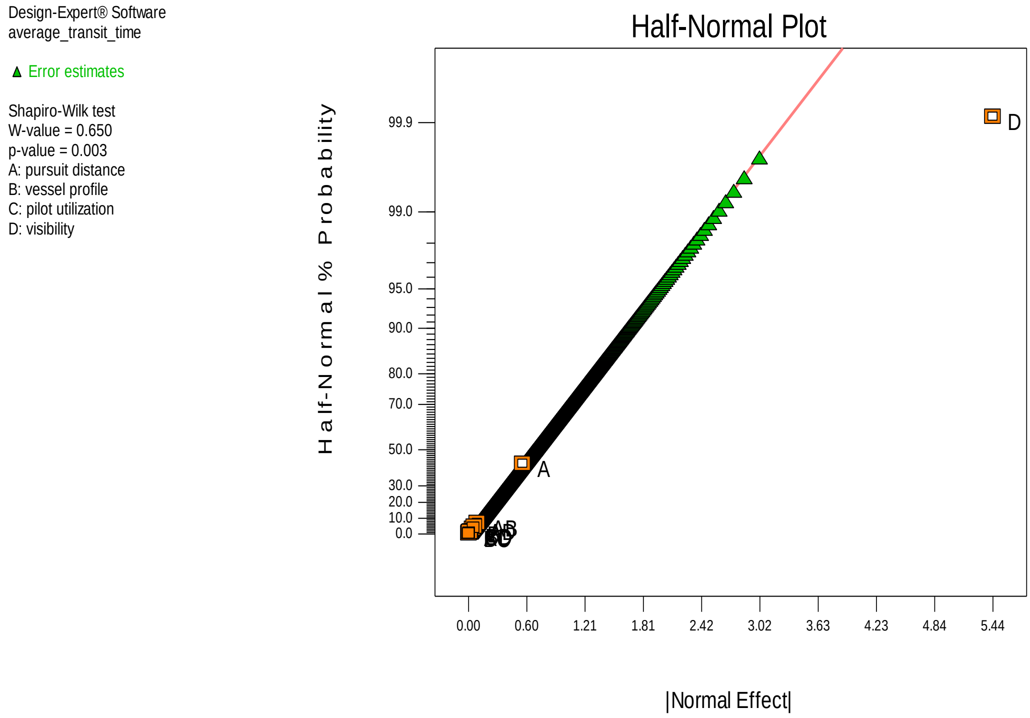


Figure 5.14. Half-normal probability plot for the effects of vessel transit time under high arrival rate

The significant factors affecting the vessel transit time is determined by analyzing the related ANOVA table (Table D.7). According to this table, the Model F-value of 2.14 implies that the model is significant. “Prob>F values less than 0.05” indicate that the model terms are significant. In this regard, only D is the significant model term. Contribution of this significant factor calculated by means of the mean square proportion is displayed in Table 5.20.

Table 5.20. Percent contribution of factors to vessel transit time under high arrival rate

| Factor | % Contribution |
|---|---|
| D | 95.61 |

The only significant factor for average vessel transit time is the the visibility conditions. This factor indirectly increases transit duration through causing higher vessel density in queues, after fog disappears in the Strait. As vessel density increases, vessels less frequently overtake each other and high speed vessels are obliged to transit behind low speed ones causing longer transit times.

### 5.4. Summary of Factor Effects

When the simulation results of selected performance measures and factors effective on these results are examined, two factors; arrival rate and visibility conditions are observed to be standing out among all.

The arrival rate (D) is the dominant factor in the factor analysis discussed in Section 5.1. The average waiting time of all vessels and each vessel class average waiting time values are directly related to the increase in vessel arrivals. Furthermore, the total number of vessels passed through the Strait and accordingly the total number of northbound and southbound vessels permitted to the Strait increase as the vessel arrivals are increased by 5 per cent and 10 per cent. Furthermore, as the arrival rate increases, more pilot necessity emerges so the pilot utilization increases. Vessel density is also affected by this factor, that is, the increase in number of vessels entering the Strait, causes higher vessel density and correspondingly, transit time of vessels lengthen out, as well.

The other significant factor in section 5.1 is the minimum pursuit distance between vessels (A). Average waiting time of vessels and average waiting time of each vessel class decrease as pursuit distances are reduced. On the other hand, this decrease provides increase in total number of vessels passed through the Strait and again increases total number of vessels passed from both sides.  More frequent vessel entrance also increases the pilot utilization and vessel density.

The interaction of the mentioned factors A and D are also significant for the scenarios in section 5.1. As both factor A and factor D are set at high levels, average waiting times of all vessels increase. When factor A is at low level and factor D is at high level, the total number of vessels passed through the Strait, the pilot utilization and the vessel density increase.

The pilot availability factor (C) is also effective in some performance measures. Although it does not make high contributions to the average waiting time of vessels, as the number of pilots in the system increases, the total number of vessels passed through the Strait (and from each direction) also increases. This change in available pilot level decreases the pilot utilization.

The last significant factor is the vessel profile (B). When all vessels longer than 150 meters are required to deploy pilot captain during their transit, the total number of vessels passed from both sides decreases. Since high levels of factor B necessitates more pilots available in the system, pilot utilization increases and due to potential shortage of pilots when requested, vessel density decreases.

In section 5.2, vessel arrival rates are increased by 10 per cent and in addition to factors A, B and C, the visibility conditions factor (D) is inspected in order to understand the meteorological event changes.

In the scenario analysis of section 5.2, the most effective factor on performance measures is observed as visibility conditions. As fog in the Strait becomes stronger, average waiting time of vessels and transit time increase. Moreover, low visibility conditions decrease total number of vessels passed from both directions, pilot utilization and vessel density in the Strait. The interaction of factor A and D is also significant for performance measures. At high levels of factors A and D, total average waiting time of vessels vessel increase whereas at low levels of factors A and D, number of northbound and southbound vessels passed and pilot utilization increase.

## 5.5. Comparison of Scenario Outputs

In this section, some scenario outputs are compared in order to better understand the effects of factors. In Table 5.21, the scenarios with base, best and worst factor settings (discussed in section 5.1) are displayed and results of various performance measures are compared in Table 5.22.

Table 5.21. Factors with base, best and worst settings

| Factor | Name | Base | Best | Worst |
|---|---|---|---|---|
| A | pursuit time | 14N-12.5S | 13- 11.5 | 14N-12.5S |
| B | vessel profile | Base | base | >=150 m |
| C | pilot availability | 20 | 24 | 16 |
| D | arrival rate | Base | base | 10% more |

Table 5.22. Results of scenarios with base, best and worst settings

| Scenario | Average waiting time | Vessels passed | Vessels in queue | Transit Time | Density | Pilot utilization |
|---|---|---|---|---|---|---|
| Base | 814 | 51178 | 79.94 | 97.06 | 9.45 | 0.24 |
| Best | 536 | 51206 | 51.9 | 97.07 | 9.45 | 0.20 |
| Worst | 2288 | 56687 | 250.7 | 97.38 | 10.77 | 0.37 |

According to the above table, the average waiting time of vessels vary between 537 and 2289 minutes. Since the most important factor for this performance measure is the vessel arrival rate, the change in response values are caused by increasing the arrival rate by 10 per cent. Total number of vessels passed ranges between 51,178 and 56,687. The base and best scenario setting results are quite close to each other, since the arrival rate which is the most important factor for this response is at the same level in both of these scenarios. Number of vessels in queues is between 80 and 250; the difference in base and best scenarios are caused by the decrease in pursuit distances between vessels (allowing them to the Strait more frequently). Average transit time does not differ significantly, but because of increase in arrival rate in the worst scenario, it increases due to higher density. Pilot utilization is directly related to pilot availability; therefore it increases from 0.20 in best scenario to 0.24 in base scenario. Moreover, it is also related to both vessel profile and arrival rate so, it increases to 0.37 in the worst scenario.

In order to track the effects of factors easily, single factor level change in scenarios is investigated through the comparison of scenarios 19, 3, 7 and 16 with the base scenario 1 as can be seen in Table 5.23. Decreasing pursuit distance to 13.5 minutes for south entrances and to 12 minutes for north entrances, primarily decrease the waiting time (by 25 per cent), decrease the number of vessels in queues by 26.25 per cent, while keeping the total number of vessels passed and vessel density almost the same. Decreasing the number of available pilots from 20 to 16 increases pilot utilization by 29.2 per cent and decreases waiting time by 11.30 per cent. (the reason why the average waiting time decreases is due to decrease in waiting time of Class D vessels, which enter the Strait more frequently while other vessel types remain waiting because of pilot unavailability). Assigning pilots for all vessels longer than 150 meters increases pilot utilization by 4.1 per cent. Increasing vessel arrival rate by ten per cent increases total number of vessels passed by 10.64 per cent, average waiting time by 181 per cent, number of vessels in queues by 212 per cent, pilot utilization by 29.2 per cent and vessel density by 10.8 per cent. The effect of two and three factor level changes over responses is also investigated. As can be seen in Table 5.23, decreasing pursuit distance to 13.5 minutes for northbound and to 12 minutes for southbound vessels while assigning pilot for all vessels longer than 150 meters (scenario 25) decrease the waiting time by 18.6 per cent when compared to the base scenario; however, waiting time is increased by 9.9 per cent when compared to the single factor level change case involving 13.5 minutes pursuit distance for south entrances and 12 minutes for north entrances (scenario 19). Table 5.23 also display that increasing vessel arrival rate by ten per cent and 20 available pilots to 24 in the system while assigning pilot for all vessels longer than 150 meters (comparison of scenarios 10 and 12) decrease the waiting time by 4.62 per cent and number of vessels in queues by 5.22 per cent. Furthermore, increasing 20 available pilots to 24 in the system while assigning pilot for all vessels longer than 150 meters under five per cent higher arrival rate (comparison of scenarios 49 and 52) have almost same performance measure results.

Table 5.23. Scenarios with various factor level changes

| Scenari | Pursuit distance | Pilot | Rate | Profil | # | Queue | Density | Pilot uti | Wait |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 14N-12.5S | 20 | normal | normal | 51,178 | 79.94 | 9.45 | 0.24 | 814 |
| 19 | 13.5N-12S | 20 | normal | normal | 51,206 | 59.16 | 9.46 | 0.24 | 608 |
| 3 | 14N-12.5S | 16 | normal | normal | 51,204 | 70.26 | 9.46 | 0.31 | 722 |
| 7 | 14N-12.5S | 20 | normal | 150m | 51,200 | 73.36 | 9.45 | 0.25 | 754 |
| 4 | 14N-12.5S | 20 | 10% more | normal | 56,628 | 250.70 | 10.47 | 0.26 | 2289 |
| 10 | 14N-12.5S | 20 | 10% more | 150m | 56,624 | 249.80 | 10.47 | 0.27 | 2275 |
| 12 | 14N-12.5S | 24 | 10% more | 150m | 56,677 | 236.90 | 10.48 | 0.22 | 2170 |
| 21 | 13.5N-12S | 16 | normal | normal | 51,193 | 65.16 | 9.45 | 0.31 | 669 |
| 29 | 13.5N-12S | 20 | 5% more | normal | 53,865 | 78.27 | 9.95 | 0.25 | 764 |
| 22 | 13.5N-12S | 20 | 10% more | normal | 56,860 | 146.60 | 10.52 | 0.26 | 1339 |
| 25 | 13.5N-12S | 20 | normal | 150m | 51,193 | 64.64 | 9.45 | 0.25 | 663 |
| 24 | 13.5N-12S | 16 | 10% more | normal | 56,850 | 146.10 | 10.52 | 0.35 | 1337 |
| 27 | 13.5N-12S | 16 | normal | 150m | 51,206 | 59.92 | 9.46 | 0.33 | 616 |
| 26 | 13.5N-12S | 24 | normal | 150m | 51,190 | 65.18 | 9.45 | 0.21 | 668 |
| 48 | 13N-11.5S | 24 | 10% | 150m | 56,960 | 85.60 | 10.54 | 0.23 | 791 |
| 49 | 13N-11.5S | 24 | 5% more | 150m | 53,880 | 62.78 | 9.95 | 0.22 | 614 |
| 52 | 13N-11.5S | 20 | 5% more | normal | 53,882 | 63.67 | 9.95 | 0.25 | 622 |

Similar to the output comparisons in section 5.1, the scenarios with base, best and worst factor settings of section 5.2 are also displayed in Table 5.24 and results of various performance measures are compared in Table 5.25.

Table 5.24. Factors with base, best and worst settings under high arrival rate

| Factor | Name | Base | Best | Worst |
|---|---|---|---|---|
| A | pursuit time | 14N-12.5S | 13.5N- 12S | 14N-12.5S |
| B | vessel profile | base | base | >=150 m |
| C | pilot availability | 20 | 24 | 16 |
| D | visibility | base | base | low |

Table 5.25. Results of scenarios with base, best and worst settings

| Scenario | Average waiting time | Vessels passed | Vessels in queue | Transit Time | Density | Pilot utilization |
|---|---|---|---|---|---|---|
| Base | 2289 | 56628 | 250 | 97.2 | 10.47 | 0.26 |
| Best | 1376 | 56846 | 150 | 97.2 | 10.52 | 0.21 |
| Worst | 4250 | 56319 | 464 | 97.2 | 10.42 | 0.35 |

In the scenario analysis under high arrival rates, the average waiting time of vessels is between 1376 and 4249. The difference between the base and best scenario in this case is because of the increase in pursuit distances between vessels. Number of vessels passed the Strait ranges between 56319 and 56846 due to visibility condition change. Number of vessels in queues is between 150 and 464, the higher value being due to low visibility. The difference in base and best scenarios in this case are caused by increasing number of pilots while reducing the pursuit distances between vessels. There are no considerable differences in transit time and density. The pilot utilization changes between 0.21 and 0.35. This difference between base and best case is caused by pilot availability.

In order to track the effects of factors easily as displayed in Table 5.26, level change in scenarios is investigated compared to the base scenario 1. Decreasing pursuit distance to 13.5 minutes for north entrances and to 12 minutes for south entrances primarily decrease the waiting time by 41.5 per cent, decrease the number of vessels in queues by 41.6 per cent, while keeping the total number of vessels passed almost the same. Setting low visibility conditions increases average waiting time by 88.8 per cent yet does not significantly change the total number of vessels passed. The effect of two and three factor level changes over responses may also be investigated in this table. For example, although reducing pursuit distances to 13.5 minutes for northbound passages and 12 minutes for southbound passages and deploying 24 pilots instead of 20, the average waiting time increases by 82 per cent under low visibility conditions (comparison of scenarios 7 and 20) and number of vessels in queues increase by 91 per cent.

Table 5.26. Scenarios with various factor level changes under high arrival rate conditions

| Scena | Pursuitdistanc | Pilo | Profile | Visibilit | # Passed | | Density | Pilot | Wait |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 14N-12.5S | 20 | normal | normal | 56629 | 250 | 10.5 | 0.3 | 2289 |
| 7 | 13.5N-12S | 20 | 150m | normal | 56850 | 146 | 10.5 | 0.3 | 1367 |
| 13 | 14N-12.5S | 20 | normal | low | 56324 | 474 | 10.4 | 0.3 | 4320 |
| 15 | 14N-12.5S | 16 | normal | low | 56336 | 448 | 10.4 | 0.4 | 4087 |
| 20 | 13.5N-12S | 24 | normal | low | 56531 | 279 | 10.5 | 0.2 | 2482 |
| 23 | 13.5N-12S | 24 | 150m | low | 56615 | 262 | 10.5 | 0.2 | 2354 |

# 6. CONCLUSION

In this study, a simulation model is developed for representing the vessel traffic behavior in the Istanbul Strait. In this simulation model, maritime rules and regulations about vessel admittance, pursuit distances among vessels, priority levels of distinct vessel types and pilot requirements to diminish risk on the Strait are all considered. Moreover, adverse meteorological conditions such as fog, current and storm are imposed to the model by submodels obtained from the previous study [2].

The crucial point that discriminates this study from others is the parametric pursuit distances between consecutive entering vessels. While the set of pursuit distances (between two vessels of a vessel class, for all vessel classes) established by the VTS authorities is deployed in the base scenario, variation from this set (either increasing or decreasing various pursuit distances) are considered in different scenarios. Moreover, in this study, the length of the northbound and southbound traffic flow time windows are set based on the waiting vessel profile at each entrance of the Strait. The simulation outputs are compared with the actual 2009 data and quite satisfactory results are obtained, in particular average waiting time of vessels, which is one of the most significant performance measures for the model, is quite close to the real system.

In order to analyze the effects of various factors such as vessel arrival rate, vessel profile, pilot availability and minimum pursuit distances between vessels, on performance measures, 54 scenarios are performed with the full factorial design. The most significant factor for all selected variables is observed as the vessel arrival rate. The minimum pursuit distance between vessels is also significant for most performance measures. The interaction of arrival rate and pursuit distance is effective on the most responses, as well. Pilot availability is principally important for pilot utilization. All vessels longer than 150 meters carrying pilot causes decrease both in total number of vessels passed and vessel density.

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

The results of the study reveal that increase in vessel demand or long lasting fog conditions on the Strait lead to very dense vessel traffic, which may cause high risk on the Strait may be somewhat eased by reducing pursuit distances and / or deploying higher number of pilots. However, the risk impacts of such decision effecting vessel waiting times, pursuit distances, pilot utilization and vessel density are beyond the scope of this study.

# 7. FURTHER STUDIES

This study involves a complex simulation model which mimics the vessel transit in Istanbul Strait with regard to R&R, meteorological restrictions and pilot and tugboat service availabilities. By means of scenario analysis, the effect of current traffic policies and external parameters are evaluated for improving the performance measures.

The fitted interarrival distributions are based on vessel length and cargo types. In an extended study, other factors effective on the arrival process may be analyzed and integrated into the inputs of the model.

The mathematical model standardizes the active direction decision and vessel entrances considering number of risky vessels and minimum pursuit distances however, the risk analysis and management are held out of scope of this study. Incorporating probable vessel accidents and the consequences to the model can have a very beneficial effect for revising the policies and minimizing risk.

Lastly, after completion of Marmaray Project, the uni directional or two way directional vessel transit policies will be investigated. The comparison of performance measure of two distinct models including these flows may facilitate to come to a decision for a new maritime traffic strategy.

# APPENDIX A: ARRIVAL PROCESS RESULTS

Table A.1 Fitted interarrival distributions for vessel classes

| Vessel Type | Distribution expression | Square error | Chi square p-value |
|---|---|---|---|
| AN | 3.99e+003 * BETA(0.327, 2.57) | 0.0112 | < 0.005 |
| AS | 3.32e+003 * BETA(0.827, 5.04) | 0.0006 | 0.23 |
| BN | -0.001+EXPO( 350 ) | - | - |
| BS | 1 + 2.66e+003 * BETA(0.917, 5.58) | 0.0006 | 0.308 |
| CN | -0.001 + EXPO(106) | - | - |
| CS | EXPO(105) | 0.0002 | 0.00892 |
| DN | -0.001 + GAMM(35.5, 0.886) | 0.0001 | < 0.005 |
| DS | -0.001 + GAMM(34, 0.942) | 0.0003 | < 0.005 |
| EN | GAMM(648, 0.974) | 0.0005 | 0.487 |
| ES | GAMM(615, 0.918) | 0.0005 | 0.466 |
| PN | -0.001 + 7.63e+003 * BETA(0.519, 4.2) | 0.0013 | 0.0233 |
| PS | 8.53e+003 * BETA(0.598, 5.37 | 0.0024 | < 0.005 |

Table A.2. Pilot demand, stopover / non stopover passing and anchoring frequencies of class A vessels in arrival processes

| Vessel Class | Vessel type | Length | Pilot request rate | Stopover rate | Anchorage rate |
|---|---|---|---|---|---|
| AN | Tanker | 200-250 | 1 | 0.05 | 0.26 |
| | Tanker | 250-300 | 1 | 0.09 | 0 |
| | LNG-LPG | 200-300 | 1 | 0 | 0 |
| | Hazmat | 200-250 | 1 | 0.91 | 0 |
| | Hazmat | 250-300 | 1 | 0.98 | 0.11 |
| AS | Tanker | 200-250 | 1 | 0.03 | 0 |
| | Tanker | 250-300 | 1 | 0.08 | 0 |
| | LNG-LPG | 200-300 | 1 | 0 | 0 |
| | Hazmat | 200-250 | 1 | 0.67 | 0 |
| | Hazmat | 250-300 | 1 | 0 | 0 |

Table A.3. Pilot demand, stopover / non stopover passing and anchoring frequencies of class B vessels in arrival processes

| Vessel Class | Vessel type | Length | Pilot request rate | Stopover rate | Anchorage rate |
|---|---|---|---|---|---|
| BN | Tanker | 150-200 | 0.97 | 0.19 | 0.32 |
| | LPG-LNG | 150-200 | 1 | 0.35 | 0.25 |
| | Hazmat | 150-200 | 0.82 | 0.51 | 0.13 |
| BS | Tanker | 150-200 | 0.95 | 0.14 | 0.01 |
| | LPG-LNG | 150-200 | 1 | 0.23 | 0.01 |
| | Hazmat | 150-200 | 0.98 | 0.25 | 0 |

Table A.4. Pilot demand, stopover / non stopover passing and anchoring frequencies of class C vessels in arrival processes

| Vessel Class | Vessel type | Length | Pilot request rate | Stopover rate | Anchorage rate |
|---|---|---|---|---|---|
| CN | Tanker | 100-150 | 0.57 | 0.45 | 0.57 |
| | LPG-LNG | 50-100 | 1 | 0.52 | 0.58 |
| | LPG-LNG | 100-150 | 0.24 | 0.3 | 0.3 |
| | Hazmat | 100-150 | 0.5 | 0.69 | 0.13 |
| | Dry cargo | 150-200 | 0.77 | 0.14 | 0.26 |
| | Dry cargo | 200-250 | 0.98 | 0.11 | 0.18 |
| | Dry cargo | 250-300 | 1 | 0.75 | 0.04 |
| CS | Tanker | 100-150 | 0.53 | 0.42 | 0.02 |
| | LPG-LNG | 50-100 | 0.38 | 0.65 | 0.02 |
| | LPG-LNG | 100-150 | 0.74 | 0.39 | 0.02 |
| | Hazmat | 100-150 | 0.36 | 0.77 | 0.01 |
| | Dry cargo | 150-200 | 0.74 | 0.18 | 0.02 |
| | Dry cargo | 200-250 | 1 | 0.22 | 0 |
| | Dry cargo | 250-300 | 1 | 0.35 | 0.01 |

Table A.5. Pilot demand, stopover / non stopover passing and anchoring frequencies of class D vessels in arrival processes

| Vessel Class | Vessel type | Length | Pilot request rate | Stopover rate | Anchorage rate |
|---|---|---|---|---|---|
| DN | Dry cargo | 0-50 | 0.06 | 0.91 | 0.29 |
| | Dry cargo | 50-100 | 0.29 | 0.6 | 0.48 |
| | Dry cargo | 100-150 | 0.41 | 0.34 | 0.57 |
| DS | Dry cargo | 0-50 | 0.04 | 0.85 | 0 |
| | Dry cargo | 50-100 | 0.24 | 0.5 | 0 |
| | Dry cargo | 100-150 | 0.37 | 0.29 | 0.01 |

Table A.6. Pilot demand, stopover / non stopover passing and anchoring frequencies of class E vessels in arrival processes

| Vessel Class | Vessel type | Length | Pilot request rate | Stopover rate | Anchorage rate |
|---|---|---|---|---|---|
| EN | Tanker | 0-50 | 0.2 | 1 | 0.33 |
| | Tanker | 50-100 | 0.38 | 0.51 | 0.5 |
| | Hazmat | 50-100 | 0.08 | 0.68 | 0.66 |
| ES | Tanker | 0-50 | 0.2 | 0.9 | 0.5 |
| | Tanker | 50-100 | 0.4 | 0.6 | 0.57 |
| | Hazmat | 50-100 | 0.2 | 0.09 | 0.42 |

Table A.7. Pilot demand, stopover / non stopover passing and anchoring frequencies of class P vessels in arrival processes

| Vessel Class | Length | Pilot request rate | Stopover rate | Anchorage rate |
|---|---|---|---|---|
| PN | 0-50 | 0.5 | 0.53 | 0.62 |
| | 50-100 | 1 | 0.85 | 0 |
| | 100-150 | 0.64 | 0.79 | 0.01 |
| | 150-200 | 0.86 | 0.68 | 0.05 |
| | 200-250 | 1 | 0.73 | 0 |
| | 250-300 | 1 | 0.16 | 0 |
| PS | 0-50 | 0.5 | 0.46 | 0.62 |
| | 50-100 | 0.8 | 0.87 | 0 |
| | 100-150 | 0.65 | 0.79 | 0.01 |
| | 150-200 | 0.98 | 0.58 | 0.05 |
| | 200-250 | 1 | 0.14 | 0 |
| | 250-300 | 1 | 0.9 | 0 |

# APPENDIX B: OUTPUTS OF THE SCENARIOS

Table B.1. Average waiting time (1-27)

| | | | | | Waiting time of vessels | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | Pursuit distance | Pilot | Rate | Profile | Model | A | B | C | D | E | P |
| 1 | 14N-12.5S | 20 | normal | normal | 814 | 1395 | 1294 | 1048 | 719 | 257 | 63.8 |
| 2 | 14N-12.5S | 24 | normal | normal | 756 | 1403 | 1285 | 1039 | 633 | 258 | 63.2 |
| 3 | 14N-12.5S | 16 | normal | normal | 722 | 1414 | 1295 | 1062 | 570 | 260 | 62.1 |
| 4 | 14N-12.5S | 20 | 10% + | normal | 2288 | 2120 | 1681 | 2678 | 2433 | 298 | 76.8 |
| 5 | 14N-12.5S | 24 | 10% + | normal | 2256 | 2114 | 1685 | 2620 | 2400 | 297 | 75.5 |
| 6 | 14N-12.5S | 16 | 10% + | normal | 2193 | 2143 | 1672 | 2625 | 2298 | 302 | 75.9 |
| 7 | 14N-12.5S | 20 | normal | 150m | 753 | 1414 | 1293 | 1052 | 623 | 260 | 63.8 |
| 8 | 14N-12.5S | 24 | normal | 150m | 755 | 1400 | 1284 | 1036 | 632 | 258 | 63.5 |
| 9 | 14N-12.5S | 16 | normal | 150m | 721 | 1394 | 1308 | 1087 | 562 | 259 | 62.1 |
| 10 | 14N-12.5S | 20 | 10% + | 150m | 2275 | 2143 | 1709 | 2686 | 2406 | 300 | 76.1 |
| 11 | 14N-12.5S | 20 | 5% + | 150m | 1145 | 1550 | 1398 | 1261 | 1146 | 272 | 69.0 |
| 12 | 14N-12.5S | 24 | 10% + | 150m | 2169 | 2080 | 1642 | 2587 | 2281 | 300 | 74.0 |
| 13 | 14N-12.5S | 24 | 5% + | 150m | 1075 | 1561 | 1383 | 1269 | 1036 | 274 | 68.0 |
| 14 | 14N-12.5S | 16 | 10% + | 150m | 2230 | 2159 | 1754 | 2752 | 2310 | 301 | 75.9 |
| 15 | 14N-12.5S | 16 | 5% + | 150m | 1183 | 1600 | 1438 | 1337 | 1176 | 276 | 71.3 |
| 16 | 14N-12.5S | 20 | 5% + | normal | 1106 | 1564 | 1387 | 1267 | 1085 | 274 | 67.7 |
| 17 | 14N-12.5S | 24 | 5% + | normal | 1134 | 1555 | 1387 | 1269 | 1127 | 274 | 68.7 |
| 18 | 14N-12.5S | 16 | 5% + | normal | 1216 | 1560 | 1422 | 1318 | 1238 | 274 | 69.7 |
| 19 | 13.5N-12S | 20 | normal | normal | 608 | 1334 | 1254 | 984 | 427 | 245 | 58.2 |
| 20 | 13.5N-12S | 24 | normal | normal | 669 | 1339 | 1250 | 977 | 525 | 245 | 58.8 |
| 21 | 13.5N-12S | 16 | normal | normal | 668 | 1362 | 1261 | 1004 | 512 | 246 | 59.9 |
| 22 | 13.5N-12S | 20 | 10% + | normal | 1339 | 1891 | 1437 | 1444 | 1367 | 276 | 71.9 |
| 23 | 13.5N-12S | 24 | 10% + | normal | 1376 | 1902 | 1437 | 1472 | 1415 | 275 | 72.8 |
| 24 | 13.5N-12S | 16 | 10% + | normal | 1337 | 1928 | 1467 | 1548 | 1327 | 279 | 72.2 |
| 25 | 13.5N-12S | 20 | normal | 150m | 663 | 1335 | 1252 | 983 | 513 | 246 | 58.6 |
| 26 | 13.5N-12S | 24 | normal | 150m | 668 | 1342 | 1252 | 979 | 522 | 245 | 58.9 |
| 27 | 13.5N-12S | 16 | normal | 150m | 616 | 1387 | 1264 | 1009 | 427 | 248 | 60.3 |

Table B.2. Average waiting time (27-54)

| | | | | | Waiting time of vessels | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | Pursuit | Pilot | Rate | Profile | Model | A | B | C | D | E | P |
| 28 | 13.5N-12S | 20 | 10% + | 150m | 1367 | 1874 | 1450 | 1484 | 1398 | 277 | 70.9 |
| 29 | 13.5N-12S | 20 | 5% + | 150m | 772 | 1461 | 1312 | 1083 | 636 | 256 | 62.3 |
| 30 | 13.5N-12S | 24 | 10% + | 150m | 1363 | 1888 | 1442 | 1470 | 1395 | 276 | 71.7 |
| 31 | 13.5N-12S | 24 | 5% + | 150m | 761 | 1462 | 1305 | 1058 | 626 | 256 | 61.5 |
| 32 | 13.5N-12S | 16 | 10% + | 150m | 1262 | 1954 | 1477 | 1547 | 1207 | 280 | 71.9 |
| 33 | 13.5N-12S | 16 | 5% + | 150m | 756 | 1519 | 1322 | 1086 | 604 | 260 | 62.6 |
| 34 | 13.5N-12S | 20 | 5% + | normal | 764 | 1465 | 1311 | 1068 | 628 | 257 | 61.6 |
| 35 | 13.5N-12S | 24 | 5% + | normal | 757 | 1469 | 1303 | 1052 | 622 | 256 | 61.8 |
| 36 | 13.5N-12S | 16 | 5% + | normal | 751 | 1453 | 1321 | 1126 | 590 | 262 | 62.0 |
| 37 | 13N-11.5S | 20 | normal | normal | 541 | 1255 | 1220 | 860 | 231 | 231 | 53.7 |
| 38 | 13N-11.5S | 24 | normal | normal | 537 | 1252 | 1219 | 857 | 364 | 232 | 52.8 |
| 39 | 13N-11.5S | 16 | normal | normal | 549 | 1250 | 1251 | 935 | 358 | 237 | 53.2 |
| 40 | 13N-11.5S | 20 | 10% + | normal | 820 | 1671 | 1334 | 1086 | 693 | 268 | 63.3 |
| 41 | 13N-11.5S | 24 | 10% + | normal | 820 | 1673 | 1327 | 1076 | 696 | 268 | 64.1 |
| 42 | 13N-11.5S | 16 | 10% + | normal | 795 | 1652 | 1341 | 1139 | 638 | 269 | 61.6 |
| 43 | 13N-11.5S | 20 | normal | 150m | 536 | 1250 | 1220 | 863 | 361 | 232 | 53.5 |
| 44 | 13N-11.5S | 24 | normal | 150m | 534 | 1246 | 1222 | 863 | 358 | 230 | 52.9 |
| 45 | 13N-11.5S | 16 | normal | 150m | 556 | 1298 | 1233 | 903 | 374 | 239 | 54.9 |
| 46 | 13N-11.5S | 20 | 10% + | 150m | 809 | 1657 | 1341 | 1082 | 676 | 267 | 63.8 |
| 47 | 13N-11.5S | 20 | 5% + | 150m | 623 | 1347 | 1272 | 921 | 466 | 248 | 54.9 |
| 48 | 13N-11.5S | 24 | 10% + | 150m | 791 | 1658 | 1322 | 1079 | 652 | 264 | 63.8 |
| 49 | 13N-11.5S | 24 | 5% + | 150m | 614 | 1336 | 1266 | 913 | 455 | 246 | 54.4 |
| 50 | 13N-11.5S | 16 | 10% + | 150m | 791 | 1658 | 1322 | 1079 | 652 | 264 | 63.8 |
| 51 | 13N-11.5S | 16 | 5% + | 150m | 614 | 1336 | 1266 | 913 | 455 | 246 | 54.4 |
| 52 | 13N-11.5S | 20 | 5% + | normal | 622 | 1347 | 1270 | 923 | 464 | 247 | 54.7 |
| 53 | 13N-11.5S | 24 | 5% + | normal | 611 | 1355 | 1265 | 906 | 452 | 245 | 54.8 |
| 54 | 13N-11.5S | 16 | 5% + | normal | 751 | 1453 | 1321 | 1126 | 590 | 262 | 62.0 |

Table B.3. Outputs of the model (1-27)

| Scenario | Pursuit | Pilot | Rate | Profile | Total pass | SB | NB | Transit | queue | Density | Pilot util | Max wait |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 14N-12.5S | 20 | normal | normal | 51,178 | 25726 | 25451 | 97.06 | 79.94 | 9.45 | 0.24 | 1894 |
| 2 | 14N-12.5S | 24 | normal | normal | 51,196 | 25746 | 25450 | 97.06 | 73.79 | 9.45 | | 1319 |
| 3 | 14N-12.5S | 16 | normal | normal | 51,204 | 25755 | 25448 | 97.06 | 70.26 | 9.46 | 0.31 | 1101 |
| 4 | 14N-12.5S | 20 | 10% more | normal | 56,628 | 28407 | 28220 | 97.23 | 250.70 | 10.47 | 0.26 | 4864 |
| 5 | 14N-12.5S | 24 | 10% more | normal | 56,630 | 28411 | 28218 | 97.23 | 246.01 | 10.48 | 0.21 | 5073 |
| 6 | 14N-12.5S | 16 | 10% more | normal | 56,687 | 28455 | 28232 | 97.23 | 233.13 | 10.49 | 0.34 | 5211 |
| 7 | 14N-12.5S | 20 | normal | 150m | 51,200 | 25749 | 25451 | 97.06 | 73.36 | 9.45 | 0.25 | 1272 |
| 8 | 14N-12.5S | 24 | normal | 150m | 51,197 | 25747 | 25450 | 97.06 | 73.56 | 9.45 | 0.20 | 1364 |
| 9 | 14N-12.5S | 16 | normal | 150m | 51,203 | 25751 | 25452 | 97.06 | 70.21 | 9.46 | 0.33 | 1129 |
| 10 | 14N-12.5S | 20 | 10% more | 150m | 56,624 | 28406 | 28217 | 97.38 | 249.80 | 10.47 | 0.27 | 6845 |
| 11 | 14N-12.5S | 20 | 5% more | 150m | 53,793 | 26986 | 26806 | 97.07 | 117.90 | 9.93 | | 2485 |
| 12 | 14N-12.5S | 24 | 10% more | 150m | 56,677 | 28453 | 28224 | 97.23 | 236.90 | 10.48 | 0.22 | 5139 |
| 13 | 14N-12.5S | 24 | 5% more | 150m | 53,828 | 27015 | 26813 | 97.08 | 110.54 | 9.94 | 0.21 | 2525 |
| 14 | 14N-12.5S | 16 | 10% more | 150m | 56,706 | 28472 | 28234 | 97.23 | 243.14 | 10.49 | 0.36 | 6637 |
| 15 | 14N-12.5S | 16 | 5% more | 150m | 53,789 | 26981 | 26807 | 97.07 | 121.94 | 9.93 | 0.34 | 3023 |
| 16 | 14N-12.5S | 20 | 5% more | normal | 53,817 | 27005 | 26811 | 97.07 | 113.85 | 9.94 | 0.25 | 2459 |
| 17 | 14N-12.5S | 24 | 5% more | normal | 53,582 | 26990 | 26813 | 97.07 | 183.79 | 9.94 | 0.20 | 2719 |
| 18 | 14N-12.5S | 16 | 5% more | normal | 53,785 | 26809 | 26809 | 97.07 | 125.68 | 9.93 | 0.32 | 3430 |
| 19 | 13.5N-12S | 20 | normal | normal | 51,206 | 25758 | 25448 | 97.06 | 59.16 | 9.46 | 0.24 | 756 |
| 20 | 13.5N-12S | 24 | normal | normal | 51,191 | 25743 | 25447 | 97.06 | 65.29 | 9.45 | 0.19 | 669 |
| 21 | 13.5N-12S | 16 | normal | normal | 51,193 | 25747 | 25446 | 97.06 | 65.16 | 9.45 | 0.31 | 2028 |
| 22 | 13.5N-12S | 20 | 10% more | normal | 56,860 | 28572 | 28288 | 97.24 | 146.60 | 10.52 | 0.26 | 3945 |
| 23 | 13.5N-12S | 24 | 10% more | normal | 56,846 | 28554 | 28292 | 97.24 | 150.58 | 10.52 | 0.21 | 3812 |
| 24 | 13.5N-12S | 16 | 10% more | normal | 56,850 | 28569 | 2828 | 97.24 | 146.10 | 10.52 | 0.35 | 3569 |
| 25 | 13.5N-12S | 20 | normal | 150m | 51,193 | 25744 | 25448 | 97.06 | 64.64 | 9.45 | 0.25 | 2106 |
| 26 | 13.5N-12S | 24 | normal | 150m | 51,190 | 25742 | 25448 | 97.06 | 65.18 | 9.45 | 0.21 | 2102 |
| 27 | 13.5N-12S | 16 | normal | 150m | 51,206 | 25757 | 25448 | 97.06 | 59.92 | 9.46 | 0.33 | 789 |

Table B.4. Outputs of the model (27-54)

| Scenarios | Pilot | Rate | Profile | # Passed | NB Passed | SB Passed | Transit time | Queue | Density | Pilot util. | Max wait |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 28 | 20 | 10% more | 150m | 56,846 | 28555 | 28290 | 97.24 | 149.62 | 10.52 | 0.28 | 3953 |
| 29 | 20 | 5% more | 150m | 53,865 | 27055 | 26810 | 97.08 | 79.06 | 9.95 | 0.26 | 1347 |
| 30 | 24 | 10% more | 150m | 56,851 | 28560 | 28290 | 97.24 | 149.22 | 10.52 | 0.22 | 4003 |
| 31 | 24 | 5% more | 150m | 53,865 | 27054 | 26811 | 97.08 | 77.88 | 9.95 | 0.21 | 1361 |
| 32 | 16 | 10% more | 150m | 56,882 | 28593 | 28288 | 97.25 | 137.69 | 10.52 | 0.36 | 3472 |
| 33 | 16 | 5% more | 150m | 56,851 | 28560 | 26805 | 97.24 | 149.22 | 10.52 | 0.35 | 1261 |
| 34 | 20 | 5% more | normal | 53,865 | 27053 | 26812 | 97.08 | 78.27 | 9.95 | 0.25 | 1392 |
| 35 | 24 | 5% more | normal | 53,866 | 27056 | 26810 | 97.08 | 77.50 | 9.95 | 0.20 | 1301 |
| 36 | 16 | 5% more | normal | 53,871 | 27058 | 26812 | 97.08 | 76.89 | 9.95 | 0.33 | 1247 |
| 37 | 20 | normal | normal | 51,210 | 25760 | 25449 | 97.07 | 52.57 | 9.46 | 0.24 | 637 |
| 38 | 24 | normal | normal | 51209 | 25761 | 25448 | 97.07 | 52.20 | 9.46 | 0.20 | 632 |
| 39 | 16 | normal | normal | 51206 | 25758 | 25448 | 97.07 | 53.42 | 9.46 | 0.32 | 656 |
| 40 | 20 | 10% more | normal | 56,957 | 28679 | 28278 | 97.25 | 88.78 | 10.54 | 0.27 | 1061 |
| 41 | 24 | 10% more | normal | 56,958 | 28677 | 28281 | 97.25 | 88.79 | 10.54 | 0.22 | 1126 |
| 42 | 16 | 10% more | normal | 56,967 | 28685 | 28282 | 97.25 | 85.99 | 10.54 | 0.35 | 1062 |
| 43 | 20 | normal | 150m | 51,209 | 25759 | 25449 | 97.07 | 52.12 | 9.46 | 0.25 | 632 |
| 44 | 24 | normal | 150m | 51,206 | 25757 | 25449 | 97.07 | 51.90 | 9.46 | 0.21 | 630 |
| 45 | 16 | normal | 150m | 51,332 | 25866 | 25465 | 97.20 | 54.14 | 9.49 | 0.34 | 690 |
| 46 | 20 | 10% more | 150m | 56,960 | 28679 | 28281 | 97.25 | 87.52 | 10.54 | 0.28 | 1098 |
| 47 | 20 | 5% more | 150m | 53,881 | 27086 | 26795 | 97.09 | 63.76 | 9.95 | 0.27 | 791 |
| 48 | 24 | 10% more | 150m | 56,960 | 28675 | 28285 | 97.25 | 85.60 | 10.54 | 0.23 | 1072 |
| 49 | 24 | 5% more | 150m | 53,880 | 27086 | 26793 | 97.09 | 62.78 | 9.95 | 0.22 | 776 |
| 50 | 16 | 10% more | 150m | 56,955 | 28675 | 28279 | 97.25 | 88.26 | 10.54 | 0.37 | 1140 |
| 51 | 16 | 5% more | 150m | 53,873 | 27079 | 26793 | 97.09 | 64.93 | 9.95 | 0.35 | 771 |
| 52 | 20 | 5% more | normal | 53,882 | 27088 | 26794 | 97.09 | 63.67 | 9.95 | 0.25 | 769 |
| 53 | 24 | 5% more | normal | 53,879 | 27085 | 26794 | 97.09 | 62.52 | 9.95 | 0.21 | 744 |
| 54 | 16 | 5% more | normal | 53,878 | 27085 | 26793 | 97.09 | 64.80 | 9.95 | 0.33 | 748 |

Table B.5. Waiting time of vessels under high arrival rate

| | | | | | | Average total waiting time | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | |
| Scenar | Pursuit | Pilot | Rate | Profile | Visibility | Model | A | B | C | D | E | P |
| 1 | 14N-12.5S | 20 | 10% + | normal | base | 2289 | 2121 | 1681 | 2679 | 2434 | 298.54 | 76.84 |
| 2 | 14N-12.5S | 24 | 10% + | normal | base | 2256 | 2115 | 1686 | 2620 | 2400 | 297.49 | 75.50 |
| 3 | 14N-12.5S | 16 | 10% + | normal | base | 2194 | 2143 | 1673 | 2625 | 2298 | 302.21 | 75.93 |
| 4 | 14N-12.5S | 20 | 10% + | 150m | base | 2275 | 2143 | 1709 | 2686 | 2407 | 300.31 | 76.07 |
| 5 | 14N-12.5S | 24 | 10% + | 150m | base | 2170 | 2081 | 1642 | 2587 | 2281 | 300.02 | 73.96 |
| 6 | 14N-12.5S | 16 | 10% + | 150m | base | 2231 | 2159 | 1755 | 2752 | 2310 | 301.61 | 75.91 |
| 7 | 13.5N-12S | 20 | 10% + | normal | base | 1339 | 1892 | 1438 | 1444 | 1368 | 276.46 | 71.87 |
| 8 | 13.5N-12S | 24 | 10% + | normal | base | 1376 | 1902 | 1437 | 1473 | 1415 | 275.13 | 72.82 |
| 9 | 13.5N-12S | 16 | 10% + | normal | base | 1337 | 1928 | 1467 | 1548 | 1327 | 279.73 | 72.23 |
| 10 | 13.5N-12S | 20 | 10% + | 150m | base | 1367 | 1875 | 1450 | 1485 | 1399 | 277.11 | 70.89 |
| 11 | 13.5N-12S | 24 | 10% + | 150m | base | 1363 | 1888 | 1443 | 1471 | 1395 | 276.10 | 71.73 |
| 12 | 13.5N-12S | 16 | 10% + | 150m | base | 1262 | 1954 | 1477 | 1547 | 1208 | 280.04 | 71.95 |
| 13 | 14N-12.5S | 20 | 10% + | normal | low | 4320 | 2196 | 2188 | 4126 | 5103 | 323.78 | 93.82 |
| 14 | 14N-12.5S | 24 | 10% + | normal | low | 4459 | 2208 | 2149 | 4262 | 5282 | 320.82 | 93.98 |
| 15 | 14N-12.5S | 16 | 10% + | normal | low | 4088 | 2198 | 2388 | 4358 | 4656 | 323.50 | 94.06 |
| 16 | 14N-12.5S | 20 | 10% + | 150m | low | 4183 | 2216 | 2182 | 3997 | 4926 | 323.13 | 92.52 |
| 17 | 14N-12.5S | 24 | 10% + | 150m | low | 4484 | 2178 | 2336 | 4159 | 2434 | 323.40 | 9 |
| 18 | 14N-12.5S | 16 | 10% + | 150m | low | 4250 | 2263 | 2372 | 4468 | 2400 | 321.95 | 96.85 |
| 19 | 13.5N-12S | 20 | 10% + | normal | low | 2131 | 1793 | 1644 | 1853 | 2298 | 299.69 | 87.60 |
| 20 | 13.5N-12S | 24 | 10% + | normal | low | 2482 | 1793 | 1848 | 2052 | 2407 | 298.20 | 90.63 |
| 21 | 13.5N-12S | 16 | 10% + | normal | low | 1999 | 1912 | 1636 | 1994 | 2281 | 306.83 | 87.09 |
| 22 | 13.5N-12S | 20 | 10% + | 150m | low | 2257 | 1781 | 1769 | 2032 | 2310 | 300.06 | 89.46 |
| 23 | 13.5N-12S | 24 | 10% + | 150m | low | 2354 | 1798 | 1786 | 1983 | 1368 | 298.22 | 89.43 |
| 24 | 13.5N-12S | 16 | 10% + | 150m | low | 2141 | 1875 | 1718 | 2041 | 1415 | 305.16 | 91.77 |

Table B.6. Outputs of the model under high arrival rate

| Scenari | Pursuit | Pilot | Rate | Profile | Visibility | Vessels Passed | NB Vessels | SB Vessels | Transit Time | In Queue | Density | Pilot Utilization | Max Waiting |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 14N-12.5S | 20 | 10% + | normal | base | 56629 | 28408 | 28221 | 97.2 | 250.7 | 10.5 | 0.3 | 4864.3 |
| 2 | 14N-12.5S | 24 | 10% + | normal | base | 56630 | 28412 | 28218 | 97.2 | 246.0 | 10.5 | 0.2 | 5073.5 |
| 3 | 14N-12.5S | 16 | 10% + | normal | base | 56688 | 28456 | 28232 | 97.2 | 233.1 | 10.5 | 0.3 | 5211.7 |
| 4 | 14N-12.5S | 20 | 10% + | 150m | base | 56624 | 28407 | 28218 | 97.4 | 249.8 | 10.5 | 0.3 | 6845.1 |
| 5 | 14N-12.5S | 24 | 10% + | 150m | base | 56677 | 28453 | 28224 | 97.2 | 236.9 | 10.5 | 0.2 | 5139.4 |
| 6 | 14N-12.5S | 16 | 10% + | 150m | base | 56707 | 28473 | 28234 | 97.2 | 243.1 | 10.5 | 0.4 | 6638.0 |
| 7 | 13.5N-12S | 20 | 10% + | normal | base | 56861 | 28573 | 28288 | 97.2 | 146.6 | 10.5 | 0.3 | 3946.0 |
| 8 | 13.5N-12S | 24 | 10% + | normal | base | 56846 | 28554 | 28292 | 97.2 | 150.6 | 10.5 | 0.2 | 3812.9 |
| 9 | 13.5N-12S | 16 | 10% + | normal | base | 56850 | 28570 | 28280 | 97.2 | 146.1 | 10.5 | 0.3 | 3569.9 |
| 10 | 13.5N-12S | 20 | 10% + | 150m | base | 56846 | 28556 | 28291 | 97.2 | 149.6 | 10.5 | 0.3 | 3953.5 |
| 11 | 13.5N-12S | 24 | 10% + | 150m | base | 56852 | 28561 | 28291 | 97.2 | 149.2 | 10.5 | 0.2 | 4003.9 |
| 12 | 13.5N-12S | 16 | 10% + | 150m | base | 56882 | 28594 | 28289 | 97.2 | 137.7 | 10.5 | 0.4 | 3472.7 |
| 13 | 14N-12.5S | 20 | 10% + | normal | low | 56324 | 28182 | 28143 | 97.2 | 474.2 | 10.4 | 0.3 | 9853.6 |
| 14 | 14N-12.5S | 24 | 10% + | normal | low | 56272 | 28133 | 28139 | 97.2 | 491.0 | 10.4 | 0.2 | 9850.8 |
| 15 | 14N-12.5S | 16 | 10% + | normal | low | 56336 | 28202 | 28134 | 97.2 | 448.3 | 10.4 | 0.3 | 7024.6 |
| 16 | 14N-12.5S | 20 | 10% + | 150m | low | 56359 | 28211 | 28148 | 97.2 | 458.6 | 10.4 | 0.3 | 9855.7 |
| 17 | 14N-12.5S | 24 | 10% + | 150m | low | 56246 | 28109 | 28137 | 97.2 | 494.3 | 10.4 | 0.2 | 10092.1 |
| 18 | 14N-12.5S | 16 | 10% + | 150m | low | 56319 | 28193 | 28127 | 97.2 | 464.9 | 10.4 | 0.4 | 6833.6 |
| 19 | 13.5N-12S | 20 | 10% + | normal | low | 56675 | 28388 | 28287 | 97.2 | 237.1 | 10.5 | 0.3 | 6710.9 |
| 20 | 13.5N-12S | 24 | 10% + | normal | low | 56532 | 28245 | 28287 | 97.2 | 279.3 | 10.5 | 0.2 | 10512.2 |
| 21 | 13.5N-12S | 16 | 10% + | normal | low | 56728 | 28449 | 28279 | 97.2 | 220.5 | 10.5 | 0.3 | 7005.9 |
| 22 | 13.5N-12S | 20 | 10% + | 150m | low | 56674 | 28385 | 28289 | 97.2 | 251.8 | 10.5 | 0.3 | 10821.6 |
| 23 | 13.5N-12S | 24 | 10% + | 150m | low | 56615 | 28331 | 28285 | 97.2 | 262.8 | 10.5 | 0.2 | 2353.9 |
| 24 | 13.5N-12S | 16 | 10% + | 150m | low | 56698 | 28417 | 28281 | 97.2 | 236.1 | 10.5 | 0.4 | 6953.8 |

# APPENDIX C: ANOVA TABLES AND MODEL GRAPHS

Table C.1. ANOVA table for average waiting time of all vessels

| Source | Sum of Square | df | Mean Square | F Value | p-value Prob > F | |
|---|---|---|---|---|---|---|
| Model | 0.0482 | 8 | 0.006 | 342.43 | < 0.0001 | significant |
| A-pursuit | 0.0180 | 2 | 0.009 | 511.65 | < 0.0001 | |
| D-arrival rate | 0.0279 | 2 | 0.014 | 793.45 | < 0.0001 | |
| AD | 0.0022 | 4 | 0.001 | 32.310 | < 0.0001 | |
| Residual | 0.0236 | 1341 | 1.76E-05 | | | |
| Lack of Fit | 0.0010 | 45 | 2.23E-05 | 1.2802 | 0.1033 | significant |
| Pure Error | 0.0225 | 1296 | 1.74E-05 | | | |
| Cor Total | 0.0718 | 1349 | | | | |
| | | | | | | |
| Std. Dev. | 0.0041 | | R-Squared | 0.6714 | | |
| Mean | 0.0352 | | AdjR-Squared | 0.6694 | | |
| C.V. % | 11.895 | | PredR-Squared | 0.6669 | | |
| PRESS | 0.0239 | | Adeq Precision | 59.685 | | |

Table C.2. ANOVA table for average waiting time of Class A vessels

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F | |
|---|---|---|---|---|---|---|
| Model | 106785849 | 14 | 7627561 | 65.8790 | < 0.0001 | significant |
| A-pursuit distance | 14655736 | 2 | 7327868 | 63.2906 | < 0.0001 | |
| C-pilot | 22674.839 | 2 | 11337.42 | 0.0979 | 0.9067 | |
| D-arrival rate | 83214445 | 2 | 41607223 | 359.361 | < 0.0001 | |
| AC | 1756898 | 4 | 439224.5 | 3.7935 | 0.0045 | |
| AD | 7136094.9 | 4 | 1784024 | 15.4085 | < 0.0001 | |
| Residual | 154568037 | 1335 | 115781.3 | | | |
| Lack of Fit | 15525800 | 39 | 398097.4 | 3.7106 | < 0.0001 | significant |
| Pure Error | 139042237 | 1296 | 107285.7 | | | |
| Cor Total | 261353886 | 1349 | | | | |
| | | | | | | |
| Std. Dev. | 340.26651 | | R-Squared | 0.408587 | | |
| Mean | 1554.3242 | | Adj R-Squared | 0.402385 | | |
| C.V. % | 21.891605 | | PredR-Squared | 0.395222 | | |
| PRESS | 158060990 | | Adeq Precision | 25.49098 | | |

Table C.3. ANOVA table for average waiting time of Class B vessels

| | | | | | p-value | |
|---|---|---|---|---|---|---|
| Source | Sum of Squares | df | Mean Square | F Value | Prob > F | |
| Model | 24263340 | 8 | 3032918 | 111.15 | < 0.0001 | significant |
| A-pursuit distance | 5812580 | 2 | 2906290 | 106.51 | < 0.0001 | |
| D-arrival rate | 15744101 | 2 | 7872050 | 288.49 | < 0.0001 | |
| AD | 2706659 | 4 | 676664.9 | 24.79 | < 0.0001 | |
| Residual | 36591223 | 1341 | 27286.52 | | | |
| Lack of Fit | 2955410 | 45 | 65675.77 | 2.53 | < 0.0001 | significant |
| Pure Error | 33635813 | 1296 | 25953.56 | | | |
| Cor Total | 60854563 | 1349 | | | | |
| | | | | | | |
| Std. Dev. | 165.1863 | | R-Squared | 0.3987 | | |
| Mean | 1368.411 | | Adj R-Squared | 0.3951 | | |
| C.V. % | 12.07139 | | PredR-Squared | 0.3906 | | |
| PRESS | 37084028 | | Adeq Precision | 34.375 | | |

Table C.4. ANOVA table for average waiting time of Class C vessels

| | Sum of | | Mean | F | p-value | |
|---|---|---|---|---|---|---|
| Source | Squares | df | Square | Value | Prob > F | |
| Model | 3.62E+08 | 8 | 45300860 | 294.29 | < 0.0001 | significant |
| A-pursuit distance | 1.08E+08 | 2 | 53960833 | 350.55 | < 0.0001 | |
| D-arrival rate | 1.58E+08 | 2 | 79032569 | 513.43 | < 0.0001 | |
| AD | 96420073 | 4 | 24105018 | 156.59 | < 0.0001 | |
| Residual | 2.06E+08 | 1341 | 153928.3 | | | |
| Lack of Fit | 3459767 | 45 | 76883.71 | 0.49 | 0.9982 | not significant |
| Pure Error | 2.03E+08 | 1296 | 156603.4 | | | |
| Cor Total | 5.69E+08 | 1349 | | | | |
| | | | | | | |
| Std. Dev. | 392.3369 | | R-Squared | 0.6371 | | |
| Mean | 1277.946 | | Adj R-Squared | 0.6349 | | |
| C.V. % | 30.70058 | | PredR-Squared | 0.6322 | | |
| PRESS | 2.09E+08 | | Adeq Precision | 55.5719 | | |

Table C.5. ANOVA table for average waiting time of Class D vessels

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F | |
|---|---|---|---|---|---|---|
| Model | 350.673 | 8 | 43.834 | 256.10 | < 0.0001 | significant |
| A-pursuit distance | 132.7839 | 2 | 66.39193 | 387.91 | < 0.0001 | |
| D-arrival rate | 197.1041 | 2 | 98.55205 | 575.81 | < 0.0001 | |
| AD | 20.78504 | 4 | 5.19626 | 30.36 | < 0.0001 | |
| Residual | 229.5185 | 1341 | 0.171155 | | | |
| Lack of Fit | 6.308436 | 45 | 0.140187 | 0.81 | 0.8056 | not significant |
| Pure Error | 223.2101 | 1296 | 0.17223 | | | |
| Cor Total | 580.1915 | 1349 | | | | |
| | | | | | | |
| Std. Dev. | 0.413709 | | R-Squared | 0.6044 | | |
| Mean | 6.518144 | | Adj R-Squared | 0.6020 | | |
| C.V. % | 6.34703 | | PredR-Squared | 0.5990 | | |
| PRESS | 232.6097 | | Adeq Precision | 51.167 | | |

Table C.6. ANOVA table for average waiting time of Class E vessels

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F | |
|---|---|---|---|---|---|---|
| Model | 478015.2 | 10 | 47801.52 | 171.07 | < 0.0001 | significant |
| A-pursuit distance | 158136.4 | 2 | 79068.2 | 282.97 | < 0.0001 | |
| C-pilot availability | 4746.983 | 2 | 2373.492 | 8.49 | 0.0002 | |
| D-arrival rate | 307066.1 | 2 | 153533 | 549.47 | < 0.0001 | |
| AD | 8065.712 | 4 | 2016.428 | 7.22 | < 0.0001 | |
| Residual | 374142.4 | 1339 | 279.4193 | | | |
| Lack of Fit | 15658.46 | 43 | 364.1503 | 1.32 | 0.0843 | not significant |
| Pure Error | 358483.9 | 1296 | 276.608 | | | |
| Cor Total | 852157.6 | 1349 | | | | |
| | | | | | | |
| Std. Dev. | 16.71584 | | R-Squared | 0.5609 | | |
| Mean | 262.6228 | | Adj R-Squared | 0.5576 | | |
| C.V. % | 6.364961 | | Pred R-Squared | 0.5537 | | |
| PRESS | 380314.9 | | Adeq Precision | 47.5761 | | |

Table C.7. ANOVA table for average waiting time of Class P vessels

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F | |
|---|---|---|---|---|---|---|
| Model | 65173.25 | 8 | 8146.657 | 81.59 | < 0.0001 | significant |
| A-pursuit distance | 29242.65 | 2 | 14621.33 | 146.4438 | < 0.0001 | |
| D-arrival rate | 34255.27 | 2 | 17127.63 | 171.5464 | < 0.0001 | |
| AD | 1675.334 | 4 | 418.8335 | 4.19 | 0.0022 | |
| Residual | 133888.9 | 1341 | 99.84258 | | | |
| Lack of Fit | 3387.492 | 45 | 75.2776 | 0.74 | 0.8905 | not |
| Pure Error | 130501.4 | 1296 | 100.6955 | | | |
| Cor Total | 199062.2 | 1349 | | | | |
| | | | | | | |
| Std. Dev. | 9.992126 | | R-Squared | 0.327402 | | |
| Mean | 63.48999 | | Adj R- | 0.323389 | | |
| C.V. % | 15.73811 | | Pred R- | 0.318343 | | |
| PRESS | 135692.1 | | Adeq | 27.29135 | | |

Table C.8. ANOVA table for total number of vessels passed the Istanbul Strait

| Source | Sum of Squares | df | F Value | p-value Prob > F | |
|---|---|---|---|---|---|
| Model | 7.23E+09 | 25 | 1704.32 | < 0.0001 | significant |
| A-pursuit distance | 21404797 | 2 | 63.081 | < 0.0001 | |
| B-vessel profile | 4616879 | 1 | 27.212 | < 0.0001 | |
| C-pilot availability | 9503932 | 2 | 28.009 | < 0.0001 | |
| D-arrival rate | 7.12E+09 | 2 | 20977.3 | < 0.0001 | |
| AB | 8435072 | 2 | 24.85 | < 0.0001 | |
| AC | 16757078 | 4 | 24.69 | < 0.0001 | |
| AD | 16730010 | 4 | 24.65 | < 0.0001 | |
| BC | 9025159 | 2 | 26.59 | < 0.0001 | |
| BD | 8372650 | 2 | 24.67 | < 0.0001 | |
| CD | 16010343 | 4 | 23.59 | < 0.0001 | |
| Residual | 2.25E+08 | 1324 | | | |
| Lack of Fit | 1.24E+08 | 28 | 57.51 | < 0.0001 | significant |
| Pure Error | 1E+08 | 1296 | | | |
| Cor Total | 7.45E+09 | 1349 | | | |
| | | | | | |
| Std. Dev. | 411.8992 | | 0.9699 | | |
| Mean | 54016.14 | | 0.9693 | | |
| C.V. % | 0.762548 | | 0.9687 | | |
| PRESS | 2.34E+08 | | 112.027 | | |

Table C.9. ANOVA table for number of northbound vessels passed the Istanbul Strait

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F | |
|---|---|---|---|---|---|---|
| Model | 1.83E+09 | 45 | 40754557 | 749.3147 | < 0.0001 | significant |
| A-pursuit distance | 9760031 | 2 | 4880015 | 89.72414 | < 0.0001 | |
| B-vessel profile | 1294190 | 1 | 1294190 | 23.79502 | < 0.0001 | |
| C-pilot policy | 2778762 | 2 | 1389381 | 25.5452 | < 0.0001 | |
| D-arrival rate | 1.78E+09 | 2 | 8.88E+08 | 16319.36 | < 0.0001 | |
| AB | 2164419 | 2 | 1082210 | 19.89755 | < 0.0001 | |
| AC | 4324728 | 4 | 1081182 | 19.87865 | < 0.0001 | |
| AD | 5464713 | 4 | 1366178 | 25.1186 | < 0.0001 | |
| BC | 2524473 | 2 | 1262237 | 23.20753 | < 0.0001 | |
| BD | 2250700 | 2 | 1125350 | 20.69073 | < 0.0001 | |
| CD | 4062628 | 4 | 1015657 | 18.67391 | < 0.0001 | |
| ABC | 4483948 | 4 | 1120987 | 20.61051 | < 0.0001 | |
| ABD | 4837168 | 4 | 1209292 | 22.23409 | < 0.0001 | |
| ACD | 9982979 | 8 | 1247872 | 22.94343 | < 0.0001 | |
| BCD | 4835386 | 4 | 1208847 | 22.2259 | < 0.0001 | |
| Residual | 70923390 | 1304 | 54389.1 | | | |
| Lack of Fit | 9268601 | 8 | 1158575 | 24.35355 | < 0.0001 | significant |
| Pure Error | 61654790 | 1296 | 47573.14 | | | |
| Cor Total | 1.9E+09 | 1349 | | | | |
| Std. Dev. | 233.2147 | | R-Squared | 0.962767 | | |
| Mean | 27149.3 | | Adj R-Squared | 0.961483 | | |
| C.V. % | 0.859008 | | Pred R-Squared | 0.960094 | | |
| PRESS | 76015445 | | Adeq Precision | 73.20407 | | |

Table C.10. ANOVA table for number of southbound vessels passed the Istanbul Strait

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F | |
|---|---|---|---|---|---|---|
| Model | 1.83E+09 | 45 | 40613494 | 1224.3 | < 0.0001 | gnificant |
| A-pursuit | 2281482 | 2 | 1140741 | 34.4 | < 0.0001 | |
| B-vessel profile | 1022258 | 1 | 1022258 | 30.8 | < 0.0001 | |
| C-pilot policy | 2005383 | 2 | 1002691 | 30.2 | < 0.0001 | |
| D-arrival rate | 1.78E+09 | 2 | 8.92E+08 | 26893.7 | < 0.0001 | |
| AB | 2054022 | 2 | 1027011 | 30.9 | < 0.0001 | |
| AC | 4068905 | 4 | 1017226 | 30.7 | < 0.0001 | |
| AD | 3483788 | 4 | 870947.1 | 26.3 | < 0.0001 | |
| BC | 2004104 | 2 | 1002052 | 30.2 | < 0.0001 | |
| BD | 1941595 | 2 | 970797.3 | 29.3 | < 0.0001 | |
| CD | 3948391 | 4 | 987097.7 | 29.8 | < 0.0001 | |
| ABC | 4059204 | 4 | 1014801 | 30.6 | < 0.0001 | |
| ABD | 4191856 | 4 | 1047964 | 31.6 | < 0.0001 | |
| ACD | 8349535 | 8 | 1043692 | 31.5 | < 0.0001 | |
| BCD | 3977375 | 4 | 994343.7 | 29.9 | < 0.0001 | |
| Residual | 43255857 | 1304 | 33171.67 | | | |
| Lack of Fit | 8366666 | 8 | 1045833 | 38.8 | < 0.0001 | significant |
| Pure Error | 34889191 | 1296 | 26920.67 | | | |
| Cor Total | 1.87E+09 | 1349 | | | | |
| | | | | | | |
| Std. Dev. | 182.1309 | | R-Squared | 0.9769 | | |
| Mean | 26866.85 | | Adj R- | 0.9761 | | |
| C.V. % | 0.677902 | | Pred R- | 0.9752 | | |
| PRESS | 46361478 | | Adeq | 90.8357 | | |

Table C.11. ANOVA table for pilot utilization

| Source | Sum of | df | Mean Square | F-Value | Prob > | |
|---|---|---|---|---|---|---|
| Model | 4.164322 | 33 | 0.126192 | 99166.8 | < | significan |
| A-pursuit | 0.014131 | 2 | 0.007066 | 5552.5 | < | |
| B-vessel profile | 0.065419 | 1 | 0.065419 | 51408.7 | < | |
| C-pilot | 3.925326 | 2 | 1.962663 | 1542345 | < | |
| D-arrival rate | 0.14821 | 2 | 0.074105 | 58234.8 | < | |
| AB | 2.83E-05 | 2 | 1.41E-05 | 11.10 | < | |
| AC | 0.000654 | 4 | 0.000164 | 128.55 | < | |
| AD | 0.001644 | 4 | 0.000411 | 323.01 | < | |
| BC | 0.001921 | 2 | 0.000961 | 754.80 | < | |
| BD | 0.000124 | 2 | 6.22E-05 | 48.87 | < | |
| CD | 0.006703 | 4 | 0.001676 | 1316.93 | < | |
| ABC | 8.53E-05 | 4 | 2.13E-05 | 16.75 | < | |
| BCD | 7.54E-05 | 4 | 1.88E-05 | 14.81 | < | |
| Residual | 0.001675 | 131 | 1.27E-06 | | | |
| Lack of Fit | 0.000109 | 20 | 5.43E-06 | 4.49 | < | significan |
| Pure Error | 0.001566 | 129 | 1.21E-06 | | | |
| Cor Total | 4.165997 | 134 | | | | |
| Std. Dev. | 0.001128 | | R-Squared | 0.9996 | | |
| Mean | 0.268597 | | Adj R- | 0.9996 | | |
| C.V. % | 0.419982 | | PredR- | 0.9996 | | |
| PRESS | 0.001762 | | Adeq | 1020.5 | | |

Table C.12. ANOVA table for average vessel density in the Istanbul Strait

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F | |
|---|---|---|---|---|---|---|
| Model | 8.51 | 25 | 0.34 | 4.98 | < 0.0001 | significant |
| A-pursuit distanc | 0.13 | 2 | 0.06 | 0.97 | 0.3783 | |
| B-vessel profile | 0.02 | 1 | 0.01 | 0.24 | 0.6271 | |
| C-pilot availabilit | 0.03 | 2 | 0.01 | 0.25 | 0.7807 | |
| D-arrival rate | 8.11 | 2 | 4.05 | 59.31 | < 0.0001 | |
| AB | 0.02 | 2 | 0.01 | 0.15 | 0.8608 | |
| AC | 0.05 | 4 | 0.01 | 0.19 | 0.9403 | |
| AD | 0.056 | 4 | 0.01 | 0.20 | 0.9364 | |
| BC | 0.03 | 2 | 0.01 | 0.19 | 0.8304 | |
| BD | 0.02 | 2 | 0.01 | 0.18 | 0.8354 | |
| CD | 0.04 | 4 | 0.01 | 0.15 | 0.9635 | |
| Residual | 90.48 | 1324 | 0.06 | | | |
| Lack of Fit | 0.33 | 28 | 0.01 | 0.17 | 1.0000 | not |
| Pure Error | 90.15 | 1296 | 0.07 | | | |
| Cor Total | 98.99 | 1349 | | | | |
| Std. Dev. | 0.26 | | R-Squared | 0.086 | | |
| Mean | 97.13 | | Adj R- | 0.068 | | |
| C.V. % | 0.269 | | Pred R- | 0.049 | | |

Table C.13. ANOVA table for average transit time in the Istanbul Strait

| Source | Squares | df | Square | Value | Prob > F | |
|---|---|---|---|---|---|---|
| Model | 255.7405 | 25 | 10.22 | 1478.502 | < 0.0001 | significant |
| A-pursuit distance | 0.798498 | 2 | 0.39 | 57.70405 | < 0.0001 | |
| B-vessel profile | 0.168224 | 1 | 0.17 | 24.3136 | < 0.0001 | |
| C-pilot policy | 0.347196 | 2 | 0.17 | 25.09034 | < 0.0001 | |
| D-arrival rate | 251.6912 | 2 | 125.85 | 18188.65 | < 0.0001 | |
| AB | 0.304588 | 2 | 0.15 | 22.01123 | < 0.0001 | |
| AC | 0.609858 | 4 | 0.15 | 22.03591 | < 0.0001 | |
| AD | 0.609299 | 4 | 0.15 | 22.0157 | < 0.0001 | |
| BC | 0.327581 | 2 | 0.16 | 23.67284 | < 0.0001 | |
| BD | 0.304139 | 2 | 0.15 | 21.97885 | < 0.0001 | |
| CD | 0.579918 | 4 | 0.14 | 20.95408 | < 0.0001 | |
| Residual | 9.160638 | 1324 | 0.01 | | | |
| Lack of Fit | 4.505069 | 28 | 0.16 | 44.78944 | < 0.0001 | significant |
| Pure Error | 4.655569 | 1296 | 0.003 | | | |
| Cor Total | 264.9012 | 1349 | | | | |
| Std. Dev. | 0.08318 | | R-Squared | 0.965419 | | |
| Mean | 9.982178 | | Adj R-Squared | 0.964766 | | |
| C.V. % | 0.833285 | | PredR-Squared | 0.964047 | | |

# APPENDIX D: ANOVA TABLES AND MODEL GRAPHS FOR SCENARIO ANALYSIS UNDER HIGH ARRIVAL RATE CONDITIONS

Table D.1. ANOVA table for average waiting time of vessels under high arrival rate conditions

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F | |
|---|---|---|---|---|---|---|
| Model | 1.31E+09 | 3 | 4.37E+08 | 393.012 | < 0.0001 | significant |
| A-pursuit | 1.75E+08 | 1 | 1.75E+08 | 157.803 | < 0.0001 | |
| D-visibility | 9.88E+08 | 1 | 9.88E+08 | 889.346 | < 0.0001 | |
| AD | 1.47E+08 | 1 | 1.47E+08 | 131.888 | < 0.0001 | |
| Residual | 6.62E+08 | 596 | 1111253 | | | |
| Lack of Fit | 7119464 | 20 | 355973.2 | 0.312 | 0.9984 | not significant |
| Pure Error | 6.55E+08 | 576 | 1137477 | | | |
| Cor Total | 1.97E+09 | 599 | | | | |
| | | | | | | |
| Std. Dev. | 1054.16 | | R-Squared | 0.6642 | | |
| Mean | 1978.882 | | Adj R-Squared | 0.6625 | | |
| C.V. % | 53.27046 | | PredR-Squared | 0.6597 | | |
| PRESS | 6.71E+08 | | Adeq Precision | 42.3839 | | |

Table D.2. ANOVA table for total number of vessels passed the Strait under high arrival rate conditions

| ANOVA for selected factorial model | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| | Sum of | | Mean | F | p-value | |
| Source | Squares | df | Square | Value | Prob > F | |
| Model | 18355981 | 14 | 1311142 | 6.641 | < 0.0001 | significant |
| A- | 4908360 | 1 | 4908360 | 24.862 | < 0.0001 | |
| B-vessel | 236810.7 | 1 | 236810.7 | 1.199 | 0.2739 | |
| C-pilot | 4106973 | 2 | 2053486 | 10.401 | < 0.0001 | |
| D- | 2252898 | 1 | 2252898 | 11.411 | 0.0008 | |
| AB | 50087.21 | 1 | 50087.21 | 0.253 | 0.6147 | |
| AC | 985010.6 | 2 | 492505.3 | 2.494 | 0.0834 | |
| AD | 38978.16 | 1 | 38978.16 | 0.197 | 0.6570 | |
| BC | 1932097 | 2 | 966048.5 | 4.893 | 0.0078 | |
| BD | 436752.2 | 1 | 436752.2 | 2.212 | 0.1375 | |
| CD | 3408015 | 2 | 1704007 | 8.631 | 0.0002 | |
| Residual | 1.15E+08 | 585 | 197423.2 | | | |
| Lack of Fit | 3908139 | 9 | 434237.6 | 2.241 | 0.0182 | significant |
| Pure Error | 1.12E+08 | 576 | 193723 | | | |
| Cor Total | 1.34E+08 | 599 | | | | |
| Std. Dev. | 444.3233 | | R-Squared | 0.1371 | | |
| Mean | 56696.42 | | Adj R- | 0.1165 | | |
| C.V. % | 0.783689 | | Pred R- | 0.0923 | | |
| PRESS | 1.21E+08 | | Adeq | 9.3421 | | |

Table D.3. ANOVA table for total number of northbound vessels passed the Strait under high arrival rate conditions

| ANOVA for selected factorial model | | | | | | |
|---|---|---|---|---|---|---|
| | Sum of | | Mean | F | p-value | |
| Source | Squares | df | Square | Value | Prob > F | |
| Model | 13068558 | 14 | 933468.4 | 5.419 | < 0.0001 | Significant |
| A-pursuit distance | 4102251 | 1 | 4102251 | 23.818 | < 0.0001 | |
| B-vessel profile | 14074.73 | 1 | 14074.73 | 0.082 | 0.7751 | |
| C-pilot availability | 484993.8 | 2 | 242496.9 | 1.408 | 0.2455 | |
| D-visibility | 7986142 | 1 | 7986142 | 46.368 | < 0.0001 | |
| AB | 158.1067 | 1 | 158.1067 | 0.001 | 0.9758 | |
| AC | 28601.3 | 2 | 14300.65 | 0.083 | 0.9203 | |
| AD | 156558.1 | 1 | 156558.1 | 0.908 | 0.3408 | |
| BC | 23067.82 | 2 | 11533.91 | 0.067 | 0.9352 | |
| BD | 620.1667 | 1 | 620.1667 | 0.003 | 0.9522 | |
| CD | 272090.9 | 2 | 136045.5 | 0.789 | 0.4544 | |
| Residual | 1.01E+08 | 585 | 172232.5 | | | |
| Lack of Fit | 177075.6 | 9 | 19675.07 | 0.112 | 0.9994 | not |
| Pure Error | 1.01E+08 | 576 | 174616.3 | | | |
| Cor Total | 1.14E+08 | 599 | | | | |
| | | | | | | |
| Std. Dev. | 415.0091 | | R-Squared | 0.114813 | | |
| Mean | 28385.78 | | Adj R- | 0.093629 | | |
| C.V. % | 1.462031 | | Pred R- | 0.068837 | | |
| PRESS | 1.06E+08 | | Adeq | 7.516303 | | |

Table D.4. ANOVA table for total number of southbound vessels passed the Strait under high arrival rate conditions

| ANOVA for selected factorial model | | | | | | |
|---|---|---|---|---|---|---|
| | Sum of | | Mean | F | p-value | |
| Source | Squares | df | Square | Value | Prob > F | |
| Model | 3021719 | 14 | 215837.1 | 7.255 | < 0.0001 | significant |
| A-pursuit distance | 2143591 | 1 | 2143591 | 72.054 | < 0.0001 | |
| B-vessel profile | 25676.04 | 1 | 25676.04 | 0.863 | 0.3533 | |
| C-pilot availability | 46271.62 | 2 | 23135.81 | 0.778 | 0.4599 | |
| D-visibility | 146546.9 | 1 | 146546.9 | 4.926 | 0.0268 | |
| AB | 26626.68 | 1 | 26626.68 | 0.895 | 0.3445 | |
| AC | 41934.84 | 2 | 20967.42 | 0.705 | 0.4946 | |
| AD | 463648.4 | 1 | 463648.4 | 15.585 | < 0.0001 | |
| BC | 59628.86 | 2 | 29814.43 | 1.002 | 0.3677 | |
| BD | 36457.21 | 1 | 36457.21 | 1.226 | 0.2687 | |
| CD | 31337.32 | 2 | 15668.66 | 0.527 | 0.5908 | |
| Residual | 17403681 | 585 | 29749.88 | | | |
| Lack of Fit | 307631.6 | 9 | 34181.28 | 1.152 | 0.3241 | not significant |
| Pure Error | 17096050 | 576 | 29680.64 | | | |
| Cor Total | 20425400 | 599 | | | | |

Table D.5. ANOVA table for pilot utilization under high arrival rate conditions

| ANOVA for selected factorial model | | | | | | |
|---|---|---|---|---|---|---|
| | Sum of | | Mean | F | -value | |
| Source | Squares | df | Square | Value | rob > F | |
| Model | 1.837159 | 21 | 0.087484 | 120422.6 | 0.0001 | ignificant |
| A-pursuit distance | 0.003151 | 1 | 0.003151 | 4337.1 | 0.0001 | |
| B-vessel profile | 0.027484 | 1 | 0.027484 | 37831.8 | 0.0001 | |
| C-pilot availability | 1.791208 | 2 | 0.895604 | 1232812 | 0.0001 | |
| D-visibility | 0.01286 | 1 | 0.01286 | 17702.0 | 0.0001 | |
| AB | 2.8E-05 | 1 | 2.8E-05 | 38.600 | 0.0001 | |
| AC | 3.64E-05 | 2 | 1.82E-05 | 25.034 | 0.0001 | |
| AD | 0.000301 | 1 | 0.000301 | 414.502 | 0.0001 | |
| BC | 0.00069 | 2 | 0.000345 | 474.887 | 0.0001 | |
| BD | 3.23E-05 | 1 | 3.23E-05 | 44.441 | 0.0001 | |
| CD | 0.001307 | 2 | 0.000654 | 899.679 | 0.0001 | |
| ABC | 1.95E-06 | 2 | 9.74E-07 | 1.341 | ).2624 | |
| ABD | 8.23E-06 | 1 | 8.23E-06 | 11.334 | ).0008 | |
| ACD | 8.75E-06 | 2 | 4.38E-06 | 6.024 | ).0026 | |
| BCD | 4.28E-05 | 2 | 2.14E-05 | 29.431 | 0.0001 | |
| Residual | 0.00042 | 578 | 7.26E-07 | | | |
| Lack of Fit | 1.2E-05 | 2 | 5.98E-06 | 8.436625 | 0.0002 | significant |
| Pure Error | 0.000408 | 576 | 7.08E-07 | | | |
| Cor Total | 1.837579 | 599 | | | | |

Table D.6. ANOVA table for vessel density under high arrival rate conditions

| ANOVA for selected factorial model | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| | Sum of | | Mean | F | -value | |
| Source | Squares | df | Square | Value | rob > F | |
| Model | 0.882281 | 14 | 0.06302 | 7.690 | 0.0001 | significant |
| A-pursuit | 0.396348 | 1 | 0.396348 | 48.367 | 0.0001 | |
| B-vessel profile | 0.000665 | 1 | 0.000665 | 0.081 | .7759 | |
| C-pilot | 0.017021 | 2 | 0.008511 | 1.039 | .3546 | |
| D-visibility | 0.427827 | 1 | 0.427827 | 52.208 | 0.0001 | |
| AB | 3E-05 | 1 | 3E-05 | 0.004 | .9518 | |
| AC | 0.000731 | 2 | 0.000365 | 0.045 | .9564 | |
| AD | 0.028667 | 1 | 0.028667 | 3.498 | .0619 | |
| BC | 0.000865 | 2 | 0.000433 | 0.053 | .9486 | |
| BD | 9.45E-05 | 1 | 9.45E-05 | 0.012 | .9145 | |
| CD | 0.010032 | 2 | 0.005016 | 0.612 | .5426 | |
| Residual | 4.793838 | 585 | 0.008195 | | | |
| Lack of Fit | 0.007704 | 9 | 0.000856 | 0.103 | .9996 | not |
| Pure Error | 4.786135 | 576 | 0.008309 | | | |
| Cor Total | 5.676119 | 599 | | | | |

Table D.7. ANOVA table for transit time under high arrival rate conditions

| ANOVA for selected factorial model | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| | Sum of | | Mean | F | p-value | |
| Source | Squares | df | Square | Value | Prob > F | |
| Model | 2.382309 | 14 | 0.170165 | 2.144 | 0.0087 | significant |
| A-pursuit distance | 0.025104 | 1 | 0.025104 | 0.316 | 0.5740 | |
| B-vessel profile | 0.000139 | 1 | 0.000139 | 0.002 | 0.9666 | |
| C-pilot utilization | 0.001322 | 2 | 0.000661 | 0.008 | 0.9917 | |
| D-visibility | 2.351507 | 1 | 2.351507 | 29.631 | < 0.0001 | |
| AB | 0.000646 | 1 | 0.000646 | 0.008 | 0.9282 | |
| AC | 0.001137 | 2 | 0.000568 | 0.007 | 0.9929 | |
| AD | 0.000281 | 1 | 0.000281 | 0.004 | 0.9526 | |
| BC | 0.000553 | 2 | 0.000277 | 0.003 | 0.9965 | |
| BD | 3.61E-05 | 1 | 3.61E-05 | 0.001 | 0.9830 | |
| CD | 0.001585 | 2 | 0.000792 | 0.009 | 0.9901 | |
| Residual | 46.42567 | 585 | 0.07936 | | | |
| Lack of Fit | 0.002189 | 9 | 0.000243 | 0.00317 | 1.0000 | not |
| Pure Error | 46.42348 | 576 | 0.080596 | | | |
| Cor Total | 48.80798 | 599 | | | | |

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