Analysis and Simulation of Istanbul Strait Marine Traffic Management Strategies

Abstract

Istanbul Strait is one of the most crowded, narrowest straits in the world. More than fifty thousand ships per year (more than one ship in ten minutes in average) pass through the Istanbul Strait. It is also assumed to be the most dangerous strait in the world due to its narrowness and nature of the sea flows in the straits. Even though the number of accidents has decreased in recent years, the risk is still high. Management of Istanbul Strait is indeed a difficult job required to control many parameters. For example, opening the strait for one or two way traffic, applying different queuing strategies, or scheduling of limited number of maritime pilots affect the strait traffic. In order to see the effect of changes in management related strategies, it may not be very practical to really apply the changes in the traffic management. Simulation of marine traffic in Istanbul Strait is very important to be able to see the effects of different management strategies and possible changes affecting the marine traffic without really applying them. This paper presents a simulation model for marine traffic in Istanbul Strait. AutoMod software is used to develop the simulation model. Different queuing strategies and management related issues are analyzed in the simulation and their effects are compared in this paper.

Keywords: Marine Traffic Simulation, Marine Traffic Management, Ship Transition Simulation, Istanbul Straits

1. Introduction

The Turkish Straits that include the Istanbul, the Canakkale (Dardanelles) Straits and the Marmara Sea is the only water route between the Black Sea and the Mediterranean. The Istanbul Strait is about 31 km long, and an average of 1.5 km wide, with its narrowest place of just 698 meters, passing through the heart of the Istanbul city. Istanbul has thousands of years of history, is declared as a “World Heritage City” by UNESCO, and also selected to be a European Capital of Culture by the EU with a population of over 10 million people. As seen from Figure 1, the strait is located in the heart of Istanbul city.

Figure 1: The Istanbul Strait

The Istanbul Strait is the narrowest waterway in the world. Moreover, three different water flows (i.e., deep, surface, and inverse flows) make the navigation even more difficult. This narrow, difficult to pass channel is one of the busiest waterways in the world. Every year, more than 50,000 vessels transit the Bosporus, which makes the strait four times busier than Panama and three times busier than Suez [9]. The strait is the only waterway for countries around the Black Sea such as Russia, Ukraine, Bulgaria and Romania (will be called as Black Sea countries).
In addition to standard trade from/to the Black Sea countries, oil, natural gas reserves in the Caspian Sea region, which is estimated to be between 25 and 200 billion barrels respectively [1], increase the traffic density in the strait. The strait traffic is highly affected from oil transportation, since transportation of oil through Baku-Ceyhan Pipeline is more expensive than sea transportation (1-2 $ through pipeline, 0.5$ by sea transport, per barrel) [2], [3]. The importance of the strait for the oil transportation is emphasized in many news and articles [4]-[8]. This importance is expected to increase in the future with the expected substantial increase (i.e., an increase of 100 million tones of crude oil per year is predicted) in the export of crude oil and liquefied gas from Black Sea countries [9].

High marine traffic, the strait’s narrowness and water flows make the strait very vulnerable to accidents. For example, 189 major accidents with many near-casualties have occurred between years 1990-1997. Besides damaging the environment, in some cases people have died in the accidents. Possible accidents and their damage to the environment is a very critical issue and studied extensively [10]-[15].

With the given high traffic density, natural difficulties, and consequences of possible accidents, management of marine traffic in the strait becomes very critical. Many studies and manuals are reported about rules for effective management of marine traffic in the strait [18]-[25]. Management of marine traffic in Istanbul strait involves many decision making processes for various parameters and strategies. For example, applying two-way traffic versus one-way traffic in the strait has advantage and disadvantages. While two-way traffic decreases the ship waiting time in the queue, it increases the accident risk. On the other hand, maritime pilots travel through the strait back and forth in the ships in a two-way traffic. In one way traffic, their transportation back to the starting point in the strait should be supplied by the management using vans or busses on road traffic. Considering the traffic intensity in Istanbul, especially in rush hours, it is not difficult to see the effect of maritime pilots in the ship traffic management in the strait. There exist hybrid strategy alternative of one/two way traffic, in which traffic is two ways in some part of the strait and one-way in the rest. These alternatives should not be applied to the real case without analyzing it in simulation kind study. Similarly, different queuing techniques used by the ship traffic management for ship scheduling should be applied to a simulation model, before trying it to the real system. Thus, it is a great need to simulate marine traffic in Istanbul Strait in order to create an evaluation environment for possible factors that affect it.

Several studies have been reported for simulation of marine traffic in different straits [26] and Istanbul strait [27], [28]. In addition to many assumptions, these studies do not report analysis of different management related issues. These studies mainly focused on the estimation of ship inter-arrival time distributions and analysis of different distributions. It is also important for a simulation system to consider the rules set by the management. For example, ship traffic management has set several rules related to geographical properties of different parts of the strait and ship time.

This paper aims to create a simulation environment for marine traffic in Istanbul strait. This environment will not only evaluate the effect of different inter-arrival ship arrival distributions, but also help Istanbul Strait Traffic Management in their decisions by simulating the effects of their decisions on various strategies. Different strategies and/or parameters such as ship passing time, priority rules, waiting time etc. can be regarded and maritime traffic can also be investigated in the simulation model. Section 2 gives detailed information about marine traffic in the strait, section 3 presents the simulation model. Section 4 displays results of different scenarios implemented in the simulation model, and finally Section 5 concludes the paper.

2. Maritime Traffic in the Strait
The passage of vessels through the Turkish Straits is governed by the 1936 Montreux Convention. According to that, all merchant vessels enjoy, in principle, complete freedom of passage and navigation by day and night, without being subject to any ‘formalities’ except for sanitary controls and optional towage and pilotage services.

In 1994, Turkey introduced the “Maritime Traffic Regulations for the Turkish Straits and the Marmara Region” regarding safety of navigation and the protection of its coastal population and environment. It also established “Traffic Separation Schemes” (TSS) in the Straits, which follow corresponding International Maritime Organization (IMO) scheme.

The maritime traffic in the Turkish Straits is exceptionally dense due to the merchant traffic, coasters, fishing vessels and local traffic causing difficulties with navigation. This dense traffic includes the transport of dangerous and hazardous cargo (LNG, LPG, oil, chemicals, and other explosive and environmentally hazardous substances).

Internal vessel movement in Istanbul Strait is more than 2000 per day. The passage statistics in the Bosporus Strait are given in Figure 2 for years 2003-2006. Figure 3 displays the distribution of number of ships throughout the year 2008. This figure does not include the movement of transiting ships, leisure craft and fishing vessels.

Istanbul strait is divided into several sequential regions. Different parts of the strait have different geological properties. Most important geological parameter is the sharpness of the turn. The Istanbul Strait takes several sharp turns. At the narrowest point (Kandilli), a 45° course alteration is required. At Yenikoy, the necessary

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Figure 2: Number of ships that passed through the Strait in recent years

Figure 3: Number of ships within a year
course alteration is $80^\circ$. At the turns (Kandilli and Yenikoy) where significant course alterations have to be made, the rear and forward sights are totally blocked prior to and during the maneuver.

Factors that affect the marine traffic in the strait can be analyzed under three categories: ship, weather, and position-related factors. Arrival time, ship type, load type, length, deep draught, and pilot and tugboat requests are vessel-related factors. Visibility, intensity and direction of water flow are the weather-related factors. Position-related factors are the restrictions special to the parts of the strait due to narrowness or sharp turns. Figure 4 illustrates these factors. These factors should be considered in the simulation model.

Ships are categorized into six groups based on their size, speed, and load. These groups will be called as SG1, SG2...SG6 hereafter. In marine traffic management, there are special rules for these groups. For example, when a SG1 type ship is moving from north to south in some part of the strait (say Kandilli - Yenikoy), a SG1 or SG3 type ship cannot move in the opposite direction. Another example might be that if a SG2 type ship is in the strait, no SG2 is allowed to enter the strait in the opposite direction until it leaves the strait.

Weather related factors also affect the marine traffic. Thus, fog or water flow related rules are set by the traffic management. Examples of these rules are given in Table 1. Position-related factors also affect the marine traffic.

<table>
<thead>
<tr>
<th>Intensity of Current (IoC) (Knots)</th>
<th>Genereal Traffic</th>
<th>Min. maneu-ver speed</th>
<th>Vessels carrying dangerous loads, big vessels (over 200m), deep draught vessels (over 15m)</th>
<th>Other ships which can not provide minimum maneuver speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4≥IoC</td>
<td>Two Way</td>
<td>IoT+4’</td>
<td>That can attain the minimum maneuver speed</td>
<td>Pilot+tug</td>
</tr>
<tr>
<td>4&lt;IoC or orkoz current</td>
<td>Two Way</td>
<td>10’</td>
<td>That can not attain the minimum maneuver speed</td>
<td>Pilot+tug</td>
</tr>
<tr>
<td>6≤IoC or intense orkoz</td>
<td>One Way</td>
<td>12’</td>
<td>Can Not Enter</td>
<td>Pilot+tug</td>
</tr>
<tr>
<td>7≤IoC</td>
<td>Two Way Closed</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Weather related rules
For example, 45 degrees of turn is required around Kandilli, which is the narrowest section of the strait with 698 meters. Yeniköy requires 80 degrees of turn. The locations similar to these places include special rules.

There are also general rules to be applied. For example, the distance between two ships cannot be less than 1456 meters (8 gomina), a ship cannot pass another one unless it is necessary (for some locations it is not allowed at all), or the traffic is restricted to one way when the visibility drops down to less than 1 mile, traffic is closed in both ways when the visibility drops to less than 0.5 miles. These rules are summarized in Table 2. They may change depending on three different situations: peace, war, and possibility-of-war times.

<table>
<thead>
<tr>
<th>Rule</th>
<th>Examples of Marine Traffic Management Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rule 1</td>
<td>The distance between two ships cannot be less than 1456 meters (8 gomina)</td>
</tr>
<tr>
<td>Rule 2</td>
<td>A ship cannot pass another one unless it is necessary</td>
</tr>
<tr>
<td>Rule 3</td>
<td>It is not allowed a ship to pass the other even if it is necessary in some locations</td>
</tr>
<tr>
<td>Rule 4</td>
<td>Traffic is restricted to one way when the visibility drops less than 1 mile</td>
</tr>
<tr>
<td>Rule 5</td>
<td>Traffic is closed in both ways when the visibility drops less than 0.5 miles</td>
</tr>
<tr>
<td>Rule 6</td>
<td>Maximum speed of a ship is 10 sea miles per hour</td>
</tr>
<tr>
<td>Rule N</td>
<td>When a ship carrying hazardous or dangerous material enters the strait, no other similar type ship is allowed in the strait</td>
</tr>
</tbody>
</table>

### 3. Simulation Study

While conducting the simulation study, the steps that are suggested in [29] have been followed. These steps include:

- Problem Formulation
- Objectives and simulation plan
- Model building
- Data collection
- Distribution fit
- Coding
- Verification and validation
- Experimental design
- Production runs and analysis

At the problem formulation step, first, the problem statement has been made. Istanbul Strait Traffic Management wants to know the effect of the different strategies when the strait traffic is limited to one way. If the strait is considered as a set of machines in series with stochastic processing times, then the problem turns out to be a scheduling problem with two different job types that are having different service times and different setup times. Since the inter-arrival times, processing times and setup times are stochastic; there is no easy analytical solution to this problem. Moreover, the way the strait is modeled in this research, machines used in series, prevents using exact analytical models. Therefore simulation is an inevitable tool to analyze this problem.
The main objective of the simulation study is to evaluate different strategies when shifting the strait passage route from one direction to the other. The direction change can only occur if the strait totally cleared. Two main strategies are identified. One strategy, which is currently used, is the “Fixed Time” strategy. Under this strategy, the direction of the marine traffic in the strait is changed in predetermined time periods. Currently this time is 12 hours, meaning that, in the first half of the day the vessels are allowed to pass from Marmara to Black Sea while the other ships that are directed to go from Black sea to Marmara keep waiting.

The second strategy is the “Queue Clearance” strategy. Under this policy, the priority is given to one direction until the vessels waiting in that direction is totally cleared. To avoid the negative effect of the worst case scenario for the system, once a priority is given to one direction, new arrivals to the queue can wait for the next turn. Once the queue is cleared the priority will be given to the other direction and that direction will keep passage right until it clears its queue. Meanwhile the other queue will be accumulating.

While modeling the system, the strait is divided into 15 sections that can be regarded as machines in series. Each section can be occupied by only one vessel at a time. This ensures that the minimum distance between vessels is kept. Vessels arrive from two different resources. Then they move in to their own queues and wait there until they get warrant to pass the strait. As mentioned before only one of these queues will have passage right at a given time. Once their passage affirmed and the strait is cleared from the vessels moving in the opposite direction, they enter the strait. In the strait, a vessel advances from one section to the next section given that the vessel ahead has left her section. If the vessel ahead is not left her section then the vessels behind slows allowing enough time to the other one to clear her section. Once a vessel travels through all 15 sections in series, it leaves the system.

To simulate this system AutoMod software and its reports are used (Figure 5). Systematic approach of the AutoMod is utilized. Simulation model built in AutoMod consists of two major systems components: main process system and path mover system. In the main process system; loads (vessels), queues, counters, subprocesses, blocks and resources are employed. Different types of loads are defined to represent different types of vessels.

Figure 5: AutoMod Runtime View Environment
In path mover system two paths are defined. One path starts from Black Sea entrance and goes through the straits ending at Marmara Sea entrance. The other one extends from Marmara Sea entrance to the Black Sea entrance. The vessels travel on these paths. These two paths do not overlap. However, very large ships might run over to the other path at some critical points increasing the risk of having an accident. In addition there is a tunnel construction under the strait going on currently. Therefore Istanbul Strait Traffic Management changed the traffic from bi-directional to one way direction. The speed of the vessels and the current in the strait is controlled through path mover system. The acceleration and deceleration of the vessels are also taken into the consideration by using stochastic passage times. For each section, minimum passage time, maximum passage time and most likely passage time information have been used.

Vessel arrival times are taken from Istanbul Strait Traffic Management and grouped based on the vessel type. Inter arrival times are obtained by considering the times between the successive vessels from the same category. Since the number of vessels using the strait changes month to month, each inter-arrival times in each month are analyzed. Then the inter arrival times are fitted to different distributions. For each distribution, after finding the distribution parameter(s), Chi-square tests are performed to measure goodness of fit. It has been observed that inter arrival times can be represented by exponential distribution. As an example, the Chi-square test results of the inter arrival times of the non hazardous ships in one category moving in the direction of Marmara to Black Sea is shown in Table 3. In this category, in April, 763 vessels arrived to the strait from Marmara direction. The mean inter arrival time has been calculated 56.55 minutes. For Chi-square test, fifteen data intervals (number of bins) have been selected. For significance level (Type I error) of $\alpha = 0.05$ the critical Chi-square value, 23.6848, is obtained. Since 9.3526 is less than the critical value, the hypothesis, the inter arrivals fit into the exponential distribution with mean 56.55 minutes, is accepted.

After finding the appropriate distributions of the data to be used in simulation, coding step took place and simulation model is built with AutoMod. For verification purposes, the queues and passage of vessels are animated. The behaviors of the vessels are visually inspected.

Table 3: Statistical Distribution Fitting Results for Interarrival Times (Exponential Dist.)

<table>
<thead>
<tr>
<th>DataCount:</th>
<th>763</th>
<th>Dist. Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Bins:</td>
<td>15</td>
<td>Mean Arrival Time: 56.55 min</td>
</tr>
<tr>
<td>Year:</td>
<td>2007</td>
<td>Alpha: 0.05</td>
</tr>
<tr>
<td>Month:</td>
<td>4</td>
<td>Critical Value: 23.6848</td>
</tr>
<tr>
<td>Goodness of fit value</td>
<td>9.3526</td>
<td>Test Result: passed</td>
</tr>
</tbody>
</table>

4. Experimentation and Numerical Results

In the objective definition step, it was mentioned above that the performance of the two strait traffic control policies will be analyzed. There are several performance measurements that can be used. This study mostly concentrated on the queue statistics, such as average length, maximum length observed, and average waiting time for each direction queue. When the simulation starts there is a period where the collected statistics is not stable. After that period, system reaches a state where the critical parameters display a constant behavior. This state is called steady state. The time required to reach steady state is called warm-up period. It has been observed that as the system becomes loaded warm up period raises. For fixed time strategy with 12 hour period, the system load is lower compared to 6-hour period. 6-hour period suggests that it needs 365-days warm-up time whereas 70 days is sufficient for 12 hour period under fixed time strategy as seen in Figure 6 and Figure 7, respectively. For the periods between 6 and 12 hours, 300-days warm up period is sufficient as well. So we run the simulation
300+1000 days. First 300 days are used to get the system to steady-state. No statistics is used in first 300 hundred days of the simulation.

Figure 6: Warm up analysis when direction change time is 6 hours

Figure 7: Warm up analysis when direction change time is 12 hours

In ‘Fixed Time’ strategy, different fixed times, which is the direction alteration frequency in a day, and their effects (waiting times and the queue lengths) are analyzed. The results are depicted in Table 4. This result can also be seen in Figure 8, where the average waiting times for Marmara and Black Sea directions are graphed as well as
the total average waiting times. As it can be seen, 8 hours seems to be an optimum time period in an overall perspective. As a result of this analysis, we recommend Istanbul Strait Traffic Management to change the current 12-hour-fixed time policy to 8-hour fixed time policy. Figure 8 shows there is a linear relationship between “direction shift period” and “average waiting time” of the vessel after 10 hours of shift periods.

Table 4: Performance of the direction change periods under fixed time strategy

<table>
<thead>
<tr>
<th></th>
<th>Black Sea</th>
<th></th>
<th>Marmara</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Queue</td>
<td>Maximum Queue</td>
<td>Average Waiting Time</td>
<td>Average Queue</td>
<td>Maximum Queue</td>
</tr>
<tr>
<td>5 hours</td>
<td>3613.97</td>
<td>6762</td>
<td>71990.40</td>
<td>76.38</td>
<td>265</td>
</tr>
<tr>
<td>5.5 hours</td>
<td>1214.68</td>
<td>2035</td>
<td>24227.60</td>
<td>20.51</td>
<td>91</td>
</tr>
<tr>
<td>6 hours</td>
<td>32.58</td>
<td>139</td>
<td>650.80</td>
<td>15.32</td>
<td>84</td>
</tr>
<tr>
<td>7 hours</td>
<td>16.30</td>
<td>102</td>
<td>325.11</td>
<td>12.80</td>
<td>66</td>
</tr>
<tr>
<td>8 hours</td>
<td><strong>14.18</strong></td>
<td><strong>63</strong></td>
<td><strong>283.74</strong></td>
<td><strong>12.90</strong></td>
<td><strong>59</strong></td>
</tr>
<tr>
<td>9 hours</td>
<td>14.81</td>
<td>65</td>
<td>295.70</td>
<td>13.85</td>
<td>51</td>
</tr>
<tr>
<td>10 hours</td>
<td>15.68</td>
<td>58</td>
<td>311.98</td>
<td>14.90</td>
<td>64</td>
</tr>
<tr>
<td>11 hours</td>
<td>16.54</td>
<td>61</td>
<td>330.64</td>
<td>16.03</td>
<td>66</td>
</tr>
<tr>
<td>12 hours</td>
<td>17.67</td>
<td>72</td>
<td>352.59</td>
<td>16.93</td>
<td>63</td>
</tr>
<tr>
<td>13 hours</td>
<td>18.66</td>
<td>69</td>
<td>373.00</td>
<td>17.91</td>
<td>70</td>
</tr>
<tr>
<td>14 hours</td>
<td>19.76</td>
<td>66</td>
<td>393.87</td>
<td>19.38</td>
<td>67</td>
</tr>
<tr>
<td>15 hours</td>
<td>20.99</td>
<td>73</td>
<td>419.50</td>
<td>20.22</td>
<td>74</td>
</tr>
<tr>
<td>16 hours</td>
<td>22.40</td>
<td>75</td>
<td>444.21</td>
<td>21.67</td>
<td>72</td>
</tr>
<tr>
<td>17 hours</td>
<td>23.57</td>
<td>84</td>
<td>470.36</td>
<td>22.73</td>
<td>78</td>
</tr>
<tr>
<td>18 hours</td>
<td>24.40</td>
<td>88</td>
<td>488.49</td>
<td>24.07</td>
<td>81</td>
</tr>
<tr>
<td>19 hours</td>
<td>26.18</td>
<td>88</td>
<td>520.88</td>
<td>25.38</td>
<td>98</td>
</tr>
<tr>
<td>20 hours</td>
<td>27.17</td>
<td>87</td>
<td>541.58</td>
<td>26.50</td>
<td>90</td>
</tr>
<tr>
<td>21 hours</td>
<td>28.10</td>
<td>92</td>
<td>560.29</td>
<td>27.85</td>
<td>95</td>
</tr>
<tr>
<td>22 hours</td>
<td>29.58</td>
<td>101</td>
<td>590.47</td>
<td>28.68</td>
<td>95</td>
</tr>
<tr>
<td>23 hours</td>
<td>30.63</td>
<td>99</td>
<td>609.92</td>
<td>30.12</td>
<td>101</td>
</tr>
<tr>
<td>24 hours</td>
<td>31.86</td>
<td>105</td>
<td>636.68</td>
<td>31.37</td>
<td>108</td>
</tr>
</tbody>
</table>
Table 4 and Figure 8 suggest that the average waiting times will exponentially grow when the shift period moves from 6 hours to the left. In that case, first black sea direction starts accumulating then Marmara direction starts accumulating. Black sea direction becomes incapable of serving vessels when the period is less than 5.5 hours. Between 5 and 5.5 hours of periods, Marmara direction is still stable and capable of sending ships through the strait while Black Sea direction queue keeps accumulating. When the period is less than 5 hours both queues will keep accumulating ships meaning that they are unstable. So the critical numbers are 5 hours and 5.5 hours for Marmara and Black sea, respectively.

Figure 9 and Figure 10 give the descriptive statistics of the strait passage times for Marmara and Black Sea directions respectively. Here, Black Sea direction almost perfectly fits into the normal distribution, while arrivals from the Marmara direction can also be considered to be normally distributed.
Descriptive Statistics

**Variable: Marmara**

Anderson-Darling Normality Test
A-Squared: 222,813
P-Value: 0,000

Mean 95,0972
StDev 9,5937
Variance 92,0390
Skewness -0,166159
Kurtosis -5,0E-01
N 93582

Minimum 67,370
1st Quartile 88,161
Median 94,292
3rd Quartile 102,093
Maximum 126,638

95% Confidence Interval for Mu
95,036 95,159
95% Confidence Interval for Sigma
9,550 9,637
95% Confidence Interval for Median
94,209 94,369

Figure 9: Descriptive statistics for Marmara entrance

Descriptive Statistics

**Variable: BlackSea**

Anderson-Darling Normality Test
A-Squared: 316,491
P-Value: 0,000

Mean 87,6024
StDev 4,7092
Variance 22,1768
Skewness -8,2E-02
Kurtosis 1,14024
N 94070

Minimum 66,736
1st Quartile 84,989
Median 87,664
3rd Quartile 90,393
Maximum 112,783

95% Confidence Interval for Mu
87,572 87,632
95% Confidence Interval for Sigma
4,688 4,731
95% Confidence Interval for Median
87,632 87,698

Figure 10: Descriptive statistics for Black Sea entrance
The mean and the variance of passing times of vessels coming from Black Sea are much less than the Marmara sea direction. One might expect shorter queues in Black Sea direction. However, it becomes clearer that the queue length of Black Sea is longer as the system-load gets heavier (i.e., for period less than 8 hours.) This mainly is due to the delays that occur during changes in passing direction as the vessels wait for the strait to clear from the vessels that comes from the other direction.

After finding the optimum shift time under Fixed Time strategy, the Queue Clearance strategy is evaluated. Different versions of queue clearance strategy could have been applied. The simplest version can be called Pure Queue Clearance strategy. Under the pure version, no restriction has been put on the maximum passage right time for one direction. This type of application is the worst of all the versions of this strategy in terms of waiting time for a vessel for the worst case scenario. Therefore, ideally, it would be appropriate to put a maximum time on the passage undertaking to avoid deadlocks in the system and “starving” effects in the queues.

The average time under Pure Queue Clearance strategy has been observed to be less than the waiting time under the Fixed Time strategy regardless of which direction change period is selected. The maximum queue lengths and maximum time spent in the queues were acceptable. During 365 days of the simulation, maximum 54 vessels in southbound queue, 52 vessels on the northbound queue, and 65 vessels in both queues simultaneously have been
observed. Therefore no effect of deadlocking or “queue starvation” has been observed in the system. When the average queue lengths and average queue times are compared, it can be seen that the Queue Clearance strategy has performed better than Fixed Time strategy with optimum direction change time. As a result, usage of ‘Queue Clearance’ strategy might be recommended to traffic managements of one way straits, instead of ‘Fixed Time’ strategy. However, in practice, there will be always an upper time limit on the ownership of passage right for any direction even if the Queue Clearance strategy employed in the strait. Therefore, a good rational strategy is expected to be at somewhere between ‘Pure Queue Clearance’ strategy and ‘Fixed Time’ strategy.

5. Conclusion

A simulation model of marine traffic in Istanbul Strait is presented in this paper in order to evaluate different management strategies for Istanbul Strait traffic management. Istanbul Strait is one of the most crowded, narrowest, and most difficult to pass waterways in the world. Simulation of marine traffic in Istanbul Strait is very important to be able to see the effects of different management strategies and possible changes in the parameters that affect the marine traffic. Different traffic management strategies are analyzed in this study. As a result of this simulation study, we recommend Istanbul Strait Management to apply ‘Queue Clearance’ strategy, in which all vessels waiting in the queue is cleared before switching the one-way traffic to the opposite direction. We also recommend switching to 8-hour fixed time strategy from the currently used 12-hour-fixed time strategy if fixed time strategy is insisted.

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Acknowledgement

This work is supported by the Scientific Research Fund of Fatih University and Istanbul Strait Traffic Management under the project number P50050901_1”