Utilization of Full-Mission Ship-Handling Simulators for Navigational Risk Assessment: A Case Study of Large Vessel Passage through the Istanbul Strait

Yusuf Volkan Aydogdu

Abstract: The MV Ever Given accident, which took place in the Suez Canal in March 2021, showed the financial consequences of marine accidents in narrow channels as vessel sizes increase continuously. Fortunately, this incident did not threaten life nor the environment. Nevertheless, it has shown the need for a thorough investigation of large vessel passages through narrow channels and confined waterways. In this study, the utilization of a bridge simulator for risk assessment and determining safety criteria through the Istanbul Strait, which is one of the most critical and difficult waterways to navigate in the world, is given as a case study. In the literature, there are some studies illustrating the navigational difficulties and proposed countermeasures. However, there has been no study conducted to determine the safe passage conditions of large vessels in the Istanbul Strait. Hence, a Full-Mission Ship-Handling Simulator (FMSHS) was used to simulate the passage of large vessels in the Istanbul Strait. Scenarios were prepared and executed together with Strait Maritime Pilots to ensure the realism. After the scenarios were simulated, the outputs of each scenario were analyzed using the Environmental Stress (ES) model to highlight levels of risk that occur during the passage of large vessels, and finally, the necessary measures are recommended to mitigate the risk.

Keywords: Istanbul Strait; navigational risk analysis; large vessel; tug assistance; maritime traffic

1. Introduction

The large-sized ships built in the 1970s and 1980s have been sized or broken into pieces which have prevented the increase of mass production until the technological and economic developments of the new millennium. Over the past few years, not only container ships, but also passenger and bulk carriers have steadily increased in size. This development is mainly due to globalization, which increases the demand to transport more and more goods and people. However, the increasing size of ships creates navigational and operational challenges, i.e., during passage though narrow channels or confined waterways. The MV Ever Given accident, which took place in the Suez Canal in March 2021, showed the financial consequences of marine accidents in narrow channels as vessels' sizes increase continuously [1,2]. Fortunately, this incident did not threaten life nor the environment, but showed the need for a thorough investigation of large vessel passages through narrow channels and confined waterways. The simulation of the MV Ever Given's stranding and blockage of the Suez Channel was shown all over the news, and it has been discussed deeply in various platforms via simulation studies of the Suez Channel. However, there is a big difference between simulation and simulator studies. Simulators are expensive, both in terms of cost and time, but when comparing actual vessel use, they are comparatively inexpensive and more useful/applicable for various purposes. On the other hand, simulations can be programmed with a wide variety of functions; a compressed simulator is much cheaper and can analyze a large amount of data in a short time, but lacks realism and the influence of human factors.

In this study, a full-mission bridge simulator for risk assessment and determining the safety criteria of a large vessel is used, and its performance is shown in a case study.
Furthermore, the Istanbul Strait, which is one of the most critical and difficult waterways to navigate in the world, was chosen as the research area due to the fact that it is one of the most challenging waterways in terms of navigation and is prone to marine accidents. In the literature, there are some studies illustrating the navigational difficulties and proposed countermeasures [3–7]. However, there is no study determining the safe passage conditions of large vessels in the Istanbul Strait.

**Full-Mission Bridge Simulator**

Bridge simulators are critical and compulsory training tools for Maritime Education and Training (MET) Institutions to meet the Standards of Certification, Training, and Watchkeeping for Seafarers (STCW) Convention. According to STCW Convention Code Part B, other usages of simulator applications are strongly recommended. In order to build the most realistic schemes, simulators should also account for the psychological surroundings that trainers experience.

Some of the different usages of bridge simulators were demonstrated in Gong et al. [8], Gray [9], Benedict et al. [10], Xiufeng et al. [11], and Barsan [12]. The IMO [13] defines the simulation in the simulator as “Close to real replicas of equipment, systems, phenomenon or process. It is normally a mathematical or algorithmic model, combined with a set of initial conditions that allows prediction, visualization and control with a change in time and the model allows easy manipulation of the conditions and parameters”. Furthermore, simulation fidelity is defined as the degree to which a simulation represents the real equipment, system, process, and environment.

Simulator fidelity or behavioral realism can be described as the extent to which a simulation resembles the real equipment, system, process, and environment. In order to achieve higher fidelity, the simulator should be quite close to the representation of the real system. Validation, on the other hand, can be described as the development of appraising the stated characteristics of a simulator or simulation against a set of predetermined criteria.

Simulators should be as close as possible to a real replica of the equipment, while at the same time accounting for the real limitations of the system or processes. The combination of an analytical or numerical model with a set of initial conditions allows for prediction, visualization, and control with a change in time; under these conditions, the model should realistically perform the manipulation of the conditions and parameters.

According to the performance standards of the simulators provided by IMO STCW Code A-I/12 Part 1, there is a need for the physical, behavioral, and environmental realism of the simulators. The simulation of a system means studying a tailor-made model of a system that is prepared according to actual data. Thus, experiments and alterations can be performed on the simulated system. It is almost impossible to carry out these experiments and alterations on the system itself, due to expensive operation costs and/or an inability to address the desired conditions in a real-life environment. Previous studies have shown such benefits of risk analysis for harbor environments [14]. In addition, simulation exercises provide the proper use of resources by enabling the determination and the elimination of problematic issues leading to failure, optimizing system performance, carrying out modifications, and even rebuilding the system if necessary.

The components of a simulator vary with the type and class of simulator; however, the generic components fall under the following categories [13]:

1. Behavioral realism (mathematical model for different processes and systems, such as vessels);
2. Operational environment (visual scene including objects, degree of view, motion platform);
3. Monitoring and evaluation.

The Full-Mission Ship-Handling Simulator (FMSHS) in this study has a fidelity that has been validated and confirmed by an internationally recognized organization (Det Norske Veritas). The simulator is used not only for education and training, but also for fulfilling R&D objectives [15,16]. Some examples of the research activities associated with the simu-
lator are the analysis of environmental and maneuvering difficulties in new/re-modified port constructions, port approaches, real-time navigation in the presence of obstacles, and berthing/unberthing maneuvers. This study is also another important example of the utilization of the bridge simulator for navigational risk assessment through the Istanbul Strait. The Istanbul Strait is a challenging waterway due to its rough topology, moderate to severe environmental conditions, and heavy local traffic. There are numerous research studies that have used various simulation methods in the Istanbul Strait, i.e., [7,17,18]. There are also a considerable number of studies regarding accident statistics and accident-causing factors in the Strait, i.e., [3,4,19–23]. In the existing literature, however, there is no study that utilizes a real-time ship-handling simulator with scenarios that were prepared and executed with Strait Maritime Pilots for navigational risk assessment of the entire strait passage that ensure real-world applicability. The main objective of this study is to determine safe passage requirements (determining minimum tugboat assistance) of large vessels, including emergency cases while passing through the entire Istanbul Strait by using the FMSHS.

2. Methodology

There is a certain limitation of the FMSHS, i.e., the time and manpower required for the execution of the scenarios. Therefore, a focus group interview was performed with Strait Maritime Pilots in order to determine the most critical parameters and situations during the passage of large vessels through the Strait, and worst-case scenarios were determined for the FMSHS together with Strait Maritime Pilots. In addition, while determining the scenarios and analyzing the result, fast time simulation studies performed by Yurtoren [22] and Aydogdu [23] were taken into account. According to the result of both fast time simulations after certain scenario runs of various types and sizes of vessels passing through the Istanbul Strait, the results began to repeat.

Afterwards, these scenarios were replicated for M/V X’s (a large vessel LOA: 330 m) northbound passages in the ballast condition, and southbound passages in the fully loaded condition to determine the safe passage conditions including the total bollard pull power of tugboats, whose assistance would be required in the case of emergency. Risks were analyzed for environmental and maneuvering difficulties resulting from conditions in which the planned passage took place in order to provide safe navigation in regard to coastal interactions, as well as interactions with other vessels.

2.1. Equipment Utilized in the Study

Simulators are a different concept from simulation, and they do not have a single, concrete definition [24]. There are various ways to explain them. According to IMO [13], “simulators are an excellent tool for training in the development of competence at different responsibility levels, from normal routine task performance training to complex task training to crisis management and emergencies”. Other descriptions are as follows:

- Computer software that is able to simulate real-life conditions.
- Hardware that is able to create a simulation of the environment for research and education purposes.
- An arrangement in which the systems, computers, or programs can be run by providing controllable input, using software verification, and connecting to each other via an interface.

There are different classifications of maritime simulators [15,16,25,26]. IMO has defined four different types of simulators according to identified training and assessment objectives [13]. DNV has set the standard to ensure that the simulations provided by the simulator include a convenient level of physical and behavioral realism. The FMSHS used in this study is in Category A [10] and equipped with sophisticated on-board instruments, which are the same as a real ship’s bridge. It is capable of fully simulating behavioral and physical aspects of bridge operations, as well as performing advance maneuvers in restricted waterways. The simulator system consists of two independent bridges (main
and secondary bridges), and the navigation instruments on the main bridge are connected to a computer system. The computer-generated navigation imagery is projected to a large oval screen by seven CRT projectors with a 240-degree viewing angle from the port to starboard wings.

The FMSHS has the capability of creating the desired area in the desired region and simulating the geographical and oceanographic characteristics of that region. In the process of area design, radar images and environmental factors such as depth, bank effect, port structure (cranes, fenders, bollards, lights, etc.), and meteorological and oceanographic information (current, waves, etc.) of the designated sea area provide input to perform experiments on the model in order to evaluate different strategies or to understand system behaviors. After the preparation of a 3D version of the geographic structure of a generic domain, the region's radar display detected by the ship's radar is prepared. The insertion of vessel traffic over the generated area and the scenario designation process are the final parts of the process.

Simulator scenarios made on generated marine traffic were created in the Scenario Editor Section. Furthermore, different cases of environmental conditions with more than one input (wind, current, waves, etc.) can be recorded. With these functions, it is possible to change the environmental conditions and create different scenarios. Environmental and oceanographic conditions were prepared together with experienced Maritime Pilots to ensure the realism of the scenarios. In addition, other data such as the number of tugboats, their power, and visibility were also selected together with Pilots during this phase. After completion of all the steps, the simulation scenario was ready for execution.

For the tugboat arrangement, it was possible to use different numbers and/or types of tugboats for each simulator scenario. The FMSH system allows for different types and bollard powers of tugboats from 2.500 HP (32.7 tons) to 9.600 HP (90 tons).

2.2. Environmental Stress Model

It is important to be able to assess risk levels in a waterway for the improvement of navigational safety. Maritime Traffic Engineering focuses on this fact [27]; however, there are not many models that provide a platform to carry out an extensive navigational risk analysis based on the outcome of the FMSHS study by taking into account human factors. In the study of Hara and Shinya [28], subjective judgement values as indexes manifesting the subjective degree of danger felt by ship handlers were introduced for the first time by using the FMSHS. Afterwards the “Environmental Stress” (ES) model, which is aimed to satisfy risk assessment demand and the risk assessment index, was developed by Inoue [29,30]. It is important for maritime traffic safety to measure how ship operation systems are influenced by ship–navigator–environment interactions. The ES model demonstrates safety levels by calculating ship handling difficulties imposed on mariners by topographical and traffic environments quantitatively based on the ES value, which is an index between 0 and 1000 with acceptance criteria as given in Table 1. It classified by four major rankings: “Negligible” between 0 and 500, “Marginal” between 500 and 750, “Critical” between 750 and 900, and “Catastrophic,” between 900 and 1000, by considering the environmental conditions, which are:

(i) Topographic features (land, shoals, breakwater, buoys, fishing nets, moored vessels, and other fixed or floating obstacles);
(ii) Traffic conditions (the density of other ships and traffic flow);
(iii) External disturbances (wind, current, etc.).

The ES value is calculated by the 3 steps given below:

1. Evaluation of ship handling difficulty arising from restrictions on the water area available for maneuvering. A quantitative index expressing the degree of stress forced on the mariner by topographical restriction (ES Value for Land (ES-L)) is calculated based on the Subjective Judgment of Mariners (SJM), which is derived by multiplying coefficients (pre-defined after numerous research studies with mariners by benefiting from not only the FMSHS, but also heart rate monitors, body temperature,
questionnaires, and the correlation of the size of their ship) with the Time To Collision (TTC) to any obstacles

2. Evaluation of ship handling difficulties arising from restrictions on the freedom to make collision-avoidance maneuvers. A quantitative index expressing the degree of stress forced on the mariner by traffic congestion (ES Value for Ship (ES-S)) is calculated based on multiplying the SJM by the coefficient of the TTC with surrounding ships (according to the direction of target ships).

3. Aggregate evaluation of ship handling difficulty forced by both topographical difficulties and traffic environments in which the stress value (ES Value Aggregation (ES-A)) is derived by superimposing the value of ES-L and ES-S [27,29–31].

Hence, in this research study, the ES model was selected in order analyze and illustrate the navigational difficulties and risk imposed on mariners while passing though the Istanbul Strait with large vessels in simulator environments.

Table 1. Stress values and acceptance criteria [31]. Reprinted with permission from Young-Soo Park. Copyright 2002.

| Mariner’s Subjective Judgment | Stress Value | Stress Rank | Acceptance |
|-------------------------------|--------------|-------------|------------|
| Extremely dangerous (6)       | 1000         | Catastrophic* | Unacceptable |
| Fairly dangerous (5)          | 900          | Catastrophic* | Unacceptable |
| Somewhat dangerous (4)        | 750          | Critical*    | Unacceptable |
| Neither safe nor dangerous (3)| 500          | Marginal     | Acceptable |
| Somewhat safe (2)             | <500         | Negligible   | Acceptable |
| Fairly safe (1)               | <500         | Negligible   | Acceptable |
| Extremely safe (0)            | 0            | Negligible   | Acceptable |

* The stress values were interpreted as an accident and near-miss situation, respectively.

3. General Characteristics of the Istanbul Strait

The Istanbul Strait is 17 nautical miles in length and has some hazardous elements such as 6–7 knot currents, wind, heels, and islets requiring risky maneuvers. Every day, approximately 2100 vessels (annually, over 700,000) cross between the two ends of the strait, carrying about one million people [32,33]. There are strong currents in the Istanbul Strait, and it is one of the narrowest waterways in the world. The average length of it is about 17 nautical miles along the center line. The coastal length of the Anatolian side is 19 nautical miles, while the length of the Thracian side is 30 nautical miles due to its curved structure. The widest points are in the northern part between Anadolu Lighthouse and Rumeli Lighthouse (3600 m) and in the southern part between Ahırkapı Lighthouse and İnciburnu Lighthouse (3220 m). The width in both entrances of the Strait is longer than the middle sections [34,35].

Vessels carrying out a passage through the Strait are obliged to alter their course at least 12 times. Among these, one of the riskiest places is between Kandilli and Asiyān, an area 700 m in width that requires a 45-degree turn. Another one is at Yeniköy, which requires an 80-degree course alteration. The depth for safe passage through the Istanbul Strait is about 30–60 m. The deepest point is about 110 m offshore at Kandilli. In this sense, depth is not a risk factor for vessel passage [33]. The riskiest regions in the Istanbul Strait are Sarayburnu, Kızılkule, Umuryeri, Yeniköy, Büyükliman due to shallow waters, Salacak, Kandilli, and Kızılkule due to currents, Kanlica and Yeniköy, Bebek, İstinye, Beykoz, Tarabya, and Kızılkule, and the Kuruçeşme, and Dikilitaş pier due to the capes [33,34]. There is a 25 cm level difference between the Black Sea and the Marmara Sea which cause to level and intensity differences between the Black Sea and the Marmara Sea and consequently two types of currents occur in the Istanbul Strait: surface and bottom currents. While the surface currents are flowing from the Black Sea to the Marmara Sea, the bottom currents flows from the Marmara, which has a higher salt content, to the Black Sea. Under normal conditions, the speed of surface currents varies between 0.4 knots and 4.8 knots in different regions of the Strait. If the wind blows strongly from north or northeast, the surface current
in the Istanbul Strait can accelerate to 7–8 knots, although typically, the normal speed is 3–4 knots [36]. The bottom current flows in the opposite direction at a 25–60 m average depth. The speed of this bottom current changes from 1–3 knots. The main surface currents can start to flow in opposite directions as a result of strong south or south-westerly storms. These currents are called “orkoz currents.” When orkoz currents occur, the level between the surface and bottom currents in the southern entrance of the Strait gets higher. The depths of the surface current decreases, while the level of the bottom current increases. This affects vessels with higher drafts. Furthermore, swirls or mirrors occur because the waters, which enter the curves of capes or bays located in the opposite direction of the current, follow the curve of the coastline in the opposite direction. These currents can cause accidents and dangerous situations, affecting vessels maneuvering at the capes, requiring sharp turns [33–39].

4. Simulator Exercises and Risk Evaluation

This part includes the details of the simulator exercises of the passage and emergency maneuvering scenarios that are executed by experienced Maritime Pilots of the Istanbul Strait in various conditions. Ship maneuvers were evaluated subjectively by experts taking into account all conditions and aiming to reach comprehensive results and suggestions. With consensus from Maritime Pilots, in total, eight simulator scenarios as details given in Table 2 were decided to execute for the passage of M/V X’s (a large vessel LOA: 330 m) through the Istanbul Strait. Simulator exercises were carried out while the vessel was fully loaded or in the ballast condition. Afterwards, scenario exercises were converted to various ship sizes and lengths (LOA) during the analysis process in order to understand the level of stress imposed on the mariner due to ship size. The oceanographic and meteorological inputs of the scenarios were prepared together with experienced Maritime Pilots. Wind and current data were determined according to the particular characteristics and features of the Istanbul Strait based in a focus group interview.

Table 2. Simulator exercises and summaries of scenarios.

| Scenario no | Own Ship Particulars: | Tugboats | Other Conditions |
|-------------|----------------------|----------|------------------|
| SE-1        | I 260.000 DWT VLCC (In Ballast), LOA: 322.1 m, Breadth: 56 m, Draft: 10.7 m | Two Tugboats’ Passive Escorting | Bow/Stern Thrusters – (Not Used) |
|             | II 260.000 DWT VLCC (Fully Loaded), LOA: 322.1 m, Breadth: 56 m, Draft: 20 m | | Port/Starboard Anchors – (Not Used) |
| SE-2        | II Southbound (SB)   | Two Tugboats’ Passive Escorting | Bow/Stern Thrusters – (Not Used) |
|             |                      |          | Port/Starboard Anchors – (Not Used) |
| SE-3        | II Case Study (CS)-1: | No. 1 (3000 HP–40 tons) | Bow/Stern Thrusters – (Not Used) |
|             | Steering Gear Failure, Yeniköy | No. 2 (3000 HP) | Port/Starboard Anchors – (Not Used) |
|             |                      | No. 3 (3000 HP) | | |
| SE-4        | II CS-2: Steering Gear Failure, Kandilli | No. 1 (3000 HP) | Bow/Stern Thrusters – Anchor ++ (Both Anchors Used) |
|             |                      | No. 2 (3000 HP) | | |
|             |                      | No. 3 (3000 HP) | | |
| SE-5        | II CS-3: Steering Gear Failure, Kandilli | No. 1 (4600 HP–60 tons) | Bow/Stern Thrusters – Anchor ++ |
|             |                      | No. 2 (4600 HP) | | |
|             |                      | No. 3 (3000 HP) | | |
Table 2. Cont.

| Scenario no | Own Ship | Tugboats | Other Conditions |
|-------------|----------|----------|------------------|
| SE-6        |          |          |                  |
| I           |          | No. 1 (4600 HP) | Bow/Stern Thrusters – – |
| CS-4: Engine Failure, Kandilli | No. 2 (3000 HP) | Anchors + + | |
| SE-7        |          |          |                  |
| I           |          | No. 1 (4600 HP) | Bow/Stern Thrusters – – |
| CS-5: Engine Failure, Kandilli | No. 4 (3000 HP) | Anchor + + (Single Anchor Used) | |
| SE-8        |          |          |                  |
| II          |          | No. 5 (3000 HP) | Bow/Stern Thrusters – – (Not Used) |
| SB-10 Knots | Speed Limit for Southbound Passage Is 10 Knots in the Strait | Two Tugboats’ Passive Escorting | Port/Starboard Anchors – – (Not Used) |

In this study, two out of eight simulator exercises are illustrated in detail, for example: one of the simulator scenarios of complete Strait passage (northbound and southbound) and one of the emergency scenarios.

4.1. Simulator Exercise-1

A 260,000 DWT vessel without cargo enters the Istanbul Strait from offshore Kadıköy with a speed of 10 knots. There is routine local traffic in the southern region of the Strait, and one-way vessel traffic is enforced according to the Maritime Traffic Regulations for the Turkish Straits [37]. During the northbound passage, two tugboats are engaged for passive escorting. After carrying out the simulator exercise with the 260,000 DWT LOA 330 m “Bulk Carrier” in the risk evaluation phase, stress values are calculated for 315 m and 300 ship lengths in order to understand the level of stress imposed on the mariner due to ship size. A risk graph for this type of vessel is shown in Figure 1 based on the maneuvering difficulties that may be experienced during northbound passage through the Istanbul Strait. ES-Aggregated (ES-A) in the graph indicates the cumulative stress value; ES-Ship (ES-S) indicates the stress caused by the target vessels; ES-Land (ES-L) indicates the results, based on time, of the risk values arising from difficulties created by the coastal effects.

![Figure 1. Graphic representation of maneuvering difficulties for 330 m Bulk Carrier.](image-url)

Risk ratios raised in this exercise are shown in Figure 2 for the different risk levels of the Negligible, Marginal, Critical, and Catastrophic categories. These categories are also given in Figure 2 based on the environmental stress gathered from land–ship aggregated data.
The ES-L graph gives the stress imposed on the mariners due to maneuvering difficulties that the vessel experiences by the interaction with the topographic features. Since the Marmaray Tunnel project, one-way traffic has been implemented, and maritime traffic is suspended by the Vessel Traffic Services (VTS) during the passage of a large vessel over 250 m [38]. Thus, there will be no encountering of non-stopover vessel traffic during the passage of our object vessel, and local traffic in the southern entrance region should give way or wait for the passage of non-stopover vessel passage. Therefore, we focused on the ES-L graph. During the northbound passage of the subject ship, a total of 35% Critical, 61% Marginal, and 4% Negligible risk ratios were calculated.

![Figure 2. Result graphs based on maneuvering difficulties for 330 m Bulk Carrier.](image)

The calculated risk and the stress imposed on mariners during passage through the Strait are shown in Figure 2, and schematic track representations of the subject are shown in Figure 3.

![Figure 3. Northbound schematic representation of 330 m Bulk Carrier: (a) ES-A; (b) ES-S; (c) ES-L.](image)
Accordingly, it was derived that the southern part of the Istanbul Strait is the most difficult part due to the narrow topography and sharp turns, as indicated in the schematic representation of the calculated stress values.

4.2. Simulator Exercise-3

During the southbound passage of a 260,000 DWT fully loaded vessel with engines running full ahead, a steering gear failure occurs offshore at Yeniköy after a turning order is given and the rudder stays fixed in the mid-ship position. In this emergency situation, two 40-ton bollard-pull-power tugboats carrying out passive escorting are tied up immediately. As a result of the fast-enfolding emergency situation and large-angle turns required by the region, another 40-ton bollard pull power tugboat is requested and also tied up.

A schematic representation of the maneuvers for this emergency situation is shown in Table 3, which includes schematic representations of other simulator exercises as well. The vessel is secured by engaging the main engine and three tugboats. The vessel continued her safe passage after repairing the steering gear failure. In this emergency situation, the vessel was secured by the efficient use of the outlined measures (specifically, the tugboats under full power and exerting force in the appropriate direction).

Table 3. General risk evaluation table.

| Simulator Exercise (SE) | Negligible Risk Ratio (%) | Marginal Risk Ratio (%) | Critical Risk Ratio (%) | Catastrophic Risk Ratio (%) |
|-------------------------|---------------------------|-------------------------|-------------------------|-----------------------------|
| ES-A | ES-L | ES-S | ES-A | ES-L | ES-S | ES-A | ES-L | ES-S | ES-A | ES-L | ES-S |
| SE-1 | NB-Uncontrolled | 330 m | 4 | 4 | 84 | 44 | 61 | 6 | 37 | 35 | 2 | 15 | 0 | 8 |
| SE-2 | SB-Uncontrolled | 330 m | 9 | 12 | 88 | 30 | 41 | 1 | 50 | 47 | 1 | 11 | 0 | 10 |
| SE-8 | SB-Controlled 330 m | - | 8 | - | - | 60 | - | - | 32 | - | - | 0 | - |
| SE-1 | NB-Uncontrolled | 315 m * | - | 4 | - | - | 65 | - | - | 31 | - | - | 0 | - |
| SE-1 | NB-Uncontrolled | 300 m * | - | 4 | - | - | 69 | - | - | 27 | - | - | 0 | - |
| SE-2 | SB-Uncontrolled | 315 m * | - | 13 | - | - | 55 | - | - | 32 | - | - | 0 | - |
| SE-2 | SB-Uncontrolled | 300 m * | - | 13 | - | - | 63 | - | - | 24 | - | - | 0 | - |

* Converted ship length during evaluation.

5. Results and Discussions

In this section, the passages of a 260,000 DWT vessel (northbound and southbound) are evaluated for different LOAs. In addition, the effectiveness of different pull powers of tugboat assistance during emergencies is investigated.

The ES-L value for different vessel lengths during southbound and northbound passages are calculated as shown in Figure 4. The southbound passage generally includes higher rates of Critical risk compared to the northbound passage. When the LOA of the vessel increases, Marginal risk values turn to Critical risk values, and their ratios increase as well.

After carrying out risk evaluations for the northbound and southbound passages (SE-1 and SE-2), the analysis of the southbound passage (SE-8) was repeated with an average 10 knots speed limitation as per the Strait regulation (Traffic Regulations for the Turkish Straits and the Marmara Region, 1998) [37,38], so-called controlled passage. This passage was identified as SB-Controlled and was compared to the Strait passages without any speed limit in SE-1 (NB-Uncontrolled) and SE-2 (SB-Uncontrolled). The results of this comparison are given in Figure 5 and Tables 3 and 4.
Figure 4. Comparisons of ES-L risk category ratios for LOA: 300 m/315 m/330 m.

Figure 5. Comparisons of cruising speeds for northbound and southbound passages.

Table 4. Tugboat efficiency evaluation table.

| Simulator Exercise (SE) | Tugboat Powers (T: Ton Bollard Pull Power) | Total | Result |
|-------------------------|------------------------------------------|-------|--------|
| SE-3 Loaded             | SB-Steering Gear Yeniköy 40 T 40 T 40 T | 120 T | Unsafe |
| SE-4 Loaded             | SB-Steering Gear Kandilli 40 T 40 T 40 T | 120 T | Unsafe |
| SE-5 Loaded             | SB-Steering Gear Kandilli 40 T 40 T 60 T | 140 T | Safe   |
| SE-6 Ballast            | NB-Engine Kandilli 40 T 60 T - 100 T     | 100 T | Unsafe |
| SE-7 Ballast            | NB-Engine Kandilli 40 T 40 T 60 T        | 140 T | Safe   |

The risk ratios obtained from direct passage through the Istanbul Strait are presented in Tables 3 and 4 from the results of the empirical study to determine the efficiency of tugboat usage in the simulator exercises.

6. Conclusions

This paper provided an example of how the Full-Mission Ship-Handling Simulator can be used for research such as the determination of safe navigation requirements and minimum tugboat assistance. The results clearly demonstrated that real-time simulation is convenient to assess the navigational risk of newly designed or renovated ports. There are also many other opportunities for additional research, such as determining the effects of tugboat power, bollard positions, mooring arrangements, emergency evacuation conditions on piers, and so on.

Specific findings of this research are given below:

- A 330 m LOA vessel in ballast condition completed her northbound uncontrolled (average speed: 12 knots) passage with a 35% Critical ES-L risk. A 330 m LOA fully loaded vessel completed her southbound uncontrolled (average speed: 12 knots) passage safely with a 47% ES-L Critical risk. However, a significant increase in Critical
risk ratios was observed when compared to the northbound passage. The results from this study indicated that southbound passages are more difficult than northbound passages. Thus, the exercise was repeated with controlled speed (average speed of 10 knots). As a result, the ES-L Critical risk ratio decreased to 32%. Risk evaluations of 300 m and 315 m LOA vessels indicated striking results in the subsequent exercises. Risk ratios related to a southbound uncontrolled passage of a 315 m LOA vessel that passed through the Strait safely before showed similarities to the 330 m LOA vessel carrying out controlled passage (average of 10 knots). In this context, a southbound passage of a 330 m LOA vessel can appropriately carry out a safe and controlled passage by complying with the 10-knot speed limit.

- Analyzing the activity of tugboats used in the emergency scenarios related to northbound and southbound passages, it is recommended to use at least two tugboats with a total of 140 tons of bollard pull power. The experiments carried out in the simulator also suggested that tugboats can be safely secured when the speed of the vessel is below seven knots. This valuable information, confirmed in real-life situations, is that tugboat assistance increases the safety of navigation while carrying out passive escorting, which is the current practice and compulsory requirement for vessels over 200 m in length.

Finally, the potential damage to the environment in the case of an accident or emergency was not calculated in this study, since the vessels in the simulation did not carry any dangerous cargo. However, for tankers and other vessels carrying dangerous cargo, it shall be taken into account in future studies.

**Funding:** This research received no external funding.

**Acknowledgments:** The author would like to thank Kinzo Inoue, who developed the ES model, for his excellent guidance and for giving us the opportunity to utilize the model in this study. The author would also like to thank the Maritime Pilots employed in the Istanbul Strait involved in the experimental studies for their valuable contributions.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Cha, J.; Lee, J.; Lee, C.; Kim, Y. Legal Disputes under Time Charter in Connection with the Stranding of the MV Ever Given. *Sustainability* 2021, 13, 10589. [CrossRef]
2. Tchang, G.S. The impact of ship size on ports’ nautical costs. *Marit. Policy Manag.* 2020, 47, 27–42. [CrossRef]
3. Uğurlu, Ö.; Erol, S.; Başar, E. The analysis of life safety and economic loss in marine accidents occurring in the Turkish Straits. *Marit. Policy Manag.* 2016, 43, 356–370. [CrossRef]
4. Yıldız, S.; Sönmez, V.Z.; Uğurlu, O.; Sivri, N.; Loughney, S.; Wang, J. Modelling of possible tanker accident oil spills in the Istanbul Strait in order to demonstrate the dispersion and toxic effects of oil pollution. *Environ. Monit. Assess.* 2021, 193, 1–19. [CrossRef] [PubMed]
5. Ozbas, B.; Or, I.; Uluscu, O.S.; Altiok, T. Simulation-based risk analysis of maritime transit traffic in the Strait of Istanbul. In *Marine Navigation and Safety of Sea Transportation*; CRC Press: Boca Raton, FL, USA, 2009; p. 157.
6. Uluscu, S.O.; Özbaş, B.; Altiok, T.; Or, I.; Yılmaz, T. Transit Vessel Scheduling in the Strait of Istanbul. *J. Navig.* 2009, 62, 59–77. [CrossRef]
7. Or, I.; Kahraman, I. A simulation study of the accident risk in the Istanbul Channel. *Int. J. Emerg. Manag.* 2002, 1, 110–124. [CrossRef]
8. Borlase, B.; Blume, A.L.; Landsburg, A.C. Channel design and vessel maneuverability: Next steps. *Mar. Technol. SNAME News* 2003, 40, 93–105. [CrossRef]
9. Benedict, K.; Baldauf, M.; Kirchhoff, M.; Felsenstein, C.; Herberg, S.; Dettmann, T. Investigations for inland waterway design in shiphandling simulator and computer-based assessment of the results. In Proceedings of the 13th International Navigators Simulator Lecturers Conference INSLC-13 2004, Tokyo, Japan, 16–20 August 2004; pp. 1–8.
10. Xiufeng, Z.; Biguang, H.; Yicheng, J.; Yong, Y. Simulating test of ship navigation safety evaluation using ship handling simulator. In Proceedings of the OCEANS 2005 MTS/IEEE, Washington, DC, USA, 17–23 September 2005; p. 1902.
11. IMO. *Validation of Model Training Courses*; STW 43/3/4; IMO: London, UK, 2011.
14. Bruzzone, A.G.; Mosca, R.; Revetria, R.; Rapallo, S. Risk analysis in harbor environments using simulation. *Saf. Sci.* 2000, 351–353, 75–86. [CrossRef]

15. DNV. *Standard for Certification No. 2.14 Maritime Simulator Systems*; Det Norske Veritas: Bærum, Norway, 2011; p. 3.

16. DNV. *Statement of Compliance of JMS Full Mission Ship Handling Simulator for “Class A—Standard for Certification of Maritime Simulators No.2.14, January 2011”*; Statement id No.10021619, Statement number 001/120508, Issued on 2012-05-08; Det Norske Veritas: Bærum, Norway, 2011.

17. Sarioz, K.; Narli, E. Assessment of maneuvering performance of large tankers in restricted waterways: A real-time simulation approach. *Ocean Eng.* 2003, 30, 1535–1551. [CrossRef]

18. DNV. *Standard for Certification No. 2.14 Maritime Simulator Systems*; Det Norske Veritas: Bærum, Norway, 2011; p. 3.

19. DNV. *Statement of Compliance of JMS Full Mission Ship Handling Simulator for “Class A—Standard for Certification of Maritime Simulators No.2.14, January 2011”*; Statement id No.10021619, Statement number 001/120508, Issued on 2012-05-08; Det Norske Veritas: Bærum, Norway, 2011.

20. Sarioz, K.; Narli, E. Assessment of maneuvering performance of large tankers in restricted waterways: A real-time simulation approach. *Ocean Eng.* 2003, 30, 1535–1551. [CrossRef]

21. Aydogdu, Y.V.; Yurtoren, C.; Park, J.S.; Park, Y.S. A study on local traffic management to improve marine traffic safety in the Istanbul Strait. *J. Navig.* 2012, 65, 99–112. [CrossRef]

22. DNV. *Statement of Compliance of JMS Full Mission Ship Handling Simulator for “Class A—Standard for Certification of Maritime Simulators No.2.14, January 2011”*; Statement id No.10021619, Statement number 001/120508, Issued on 2012-05-08; Det Norske Veritas: Bærum, Norway, 2011.

23. Aydogdu, Y.V. A study on local traffic management to improve marine traffic safety in the Istanbul Strait. Ph.D. Thesis, Korea Maritime University, Busan, Korea, 2010.

24. Nautical Institute. *The Work of the Harbourmaster. Three Ship Simulation Techniques for Harbour Design and Operation by Ian R; McCallum: Wallingford, CT, USA, 2012; pp. 357–364. [CrossRef]

25. Kluj, S. The relation between learning objectives and the appropriate simulator type. In Proceedings of the 5th International Conference on Engine Room Simulators ICERS5, Singapore, 18–20 September 2001.

26. Cross, S.J.; Olofsson, M. Classification of maritime simulators: The final attempt. Introducing DNV’s new standard. In Proceedings of the International Conference on Ship Maneuverability (ICSM), Orlando, FL, USA, 8–12 May 2000.

27. Toyoda, S.; Fujii, Y. Marine Traffic Engineering. *J. Navig.* 1971, 24, 24–34. [CrossRef]

28. Hara, K.; Nakamura, S. A comprehensive assessment system for the maritime traffic environment. *Saf. Sci.* 1995, 192–193, 203–215. [CrossRef]

29. Inoue, K. Rating the Quality of Ports and Harbours from the Viewpoint of Ship-handling Difficulty. In Proceedings of the 12th International Harbour Congress, 12–16 September 1999; Volume 9, pp. 203–214.

30. Inoue, K. Evaluation method of ship-handling difficulty for navigation in restricted and congested waterways. *J. Navig.* 2000, 53, 167–180. [CrossRef]

31. Park, Y.S.; Jong, J.Y.; Inoue, K. A Study on Assessment of Vessel Traffic Safety Management by Marine Traffic Flow Simulation. *J. Koras Soc. Simul.* 2002, 11, 43–55.

32. Atasoy, C. Investigation of Local Marine Traffic at Istanbul Strait. Master’s Thesis, Istanbul Technical University, Istanbul, Turkey, 2008.

33. Aydogdu, Y.V. A study on local traffic management to improve marine traffic safety in the Istanbul Strait. Ph.D. Thesis, Korea Maritime University, Busan, Korea, 2010.

34. Nautical Institute. *The Work of the Harbourmaster. Three Ship Simulation Techniques for Harbour Design and Operation by Ian R; McCallum: Wallingford, CT, USA, 2012; pp. 357–364. [CrossRef]

35. Kluj, S. The relation between learning objectives and the appropriate simulator type. In Proceedings of the 5th International Conference on Engine Room Simulators ICERS5, Singapore, 18–20 September 2001.

36. Cross, S.J.; Olofsson, M. Classification of maritime simulators: The final attempt. Introducing DNV’s new standard. In Proceedings of the International Conference on Ship Maneuverability (ICSM), Orlando, FL, USA, 8–12 May 2000.

37. Toyoda, S.; Fujii, Y. Marine Traffic Engineering. *J. Navig.* 1971, 24, 24–34. [CrossRef]

38. Hara, K.; Nakamura, S. A comprehensive assessment system for the maritime traffic environment. *Saf. Sci.* 1995, 192–193, 203–215. [CrossRef]

39. Inoue, K. Rating the Quality of Ports and Harbours from the Viewpoint of Ship-handling Difficulty. In Proceedings of the 12th International Harbour Congress, 12–16 September 1999; Volume 9, pp. 203–214.

40. Inoue, K. Evaluation method of ship-handling difficulty for navigation in restricted and congested waterways. *J. Navig.* 2000, 53, 167–180. [CrossRef]

41. Park, Y.S.; Jong, J.Y.; Inoue, K. A Study on Assessment of Vessel Traffic Safety Management by Marine Traffic Flow Simulation. *J. Koras Soc. Simul.* 2002, 11, 43–55.

42. Atasoy, C. Investigation of Local Marine Traffic at Istanbul Strait. Master’s Thesis, Istanbul Technical University, Istanbul, Turkey, 2008.

43. Aydogdu, Y.V. A study on local traffic management to improve marine traffic safety in the Istanbul Strait. Ph.D. Thesis, Korea Maritime University, Busan, Korea, 2010.

44. Nautical Institute. *The Work of the Harbourmaster. Three Ship Simulation Techniques for Harbour Design and Operation by Ian R; McCallum: Wallingford, CT, USA, 2012; pp. 357–364. [CrossRef]

45. Kluj, S. The relation between learning objectives and the appropriate simulator type. In Proceedings of the 5th International Conference on Engine Room Simulators ICERS5, Singapore, 18–20 September 2001.

46. Cross, S.J.; Olofsson, M. Classification of maritime simulators: The final attempt. Introducing DNV’s new standard. In Proceedings of the International Conference on Ship Maneuverability (ICSM), Orlando, FL, USA, 8–12 May 2000.

47. Toyoda, S.; Fujii, Y. Marine Traffic Engineering. *J. Navig.* 1971, 24, 24–34. [CrossRef]

48. Hara, K.; Nakamura, S. A comprehensive assessment system for the maritime traffic environment. *Saf. Sci.* 1995, 192–193, 203–215. [CrossRef]

49. Inoue, K. Rating the Quality of Ports and Harbours from the Viewpoint of Ship-handling Difficulty. In Proceedings of the 12th International Harbour Congress, 12–16 September 1999; Volume 9, pp. 203–214.

50. Inoue, K. Evaluation method of ship-handling difficulty for navigation in restricted and congested waterways. *J. Navig.* 2000, 53, 167–180. [CrossRef]

51. Park, Y.S.; Jong, J.Y.; Inoue, K. A Study on Assessment of Vessel Traffic Safety Management by Marine Traffic Flow Simulation. *J. Koras Soc. Simul.* 2002, 11, 43–55.

52. Atasoy, C. Investigation of Local Marine Traffic at Istanbul Strait. Master’s Thesis, Istanbul Technical University, Istanbul, Turkey, 2008.

53. Aydogdu, Y.V. A study on local traffic management to improve marine traffic safety in the Istanbul Strait. Ph.D. Thesis, Korea Maritime University, Busan, Korea, 2010.