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Proposal for Dynamic Traffic Separation Scheme to Reduce Current-Related Ship Collision Risks in the Istanbul Strait

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Abstract – The Istanbul Strait provides access to the Mediterranean and the Black Sea, which are both major arteries of world trade, by connecting Asia and Europe. As approximately 35,000 ships pass through the Istanbul Strait each year, it has significant strategic importance in the world supply chain. However, due to the chaos caused by the current ship traffic and the combination of environmental and meteorological conditions in one of the world's most dangerous waterways, maritime accidents are inevitable. In order to minimize the risk of accidents, the Istanbul Strait is divided in half by a Traffic Separation Scheme (TSS), and ship traffic is managed based on this reference line. However, as with the rest of the world, the TSS in the Istanbul Strait is also divided in half, without taking into account the geography and current regime of the Strait. Therefore, serious ship accidents caused by the current occur frequently. In this study, the most suitable TSS proposal for the Istanbul Strait was presented using ship bridge simulators. Dynamic TSS was studied using ship bridge simulators, and the pressure line-velocity change findings derived from the positive current theory in the literature were processed into simulator scenario packages and evaluated for different ship sizes. Thus, taking into account ship hydrodynamics, current regime, and maritime practice, optimum TSSs were defined for specific ship size ranges for the first time in the literature.

Keywords – Traffic Separation Scheme, Istanbul Strait Current Regime, Current-Related Ship Accidents, Ship Bridge Simulators.

I. INTRODUCTION

The Istanbul Strait is considered an important waterway worldwide due to its historical and strategic significance. It is one of the main arteries of world trade as it provides a connection between the Mediterranean and the Black Sea, and is used by approximately 35,000 ships per year as of 2022 [1]. However, the Istanbul Strait is also known as one of the world's most dangerous waterways [2]. The intensity of ship traffic, environmental and meteorological conditions, and especially the geographical structure of the strait make accidents inevitable [3]. This problem can cause not only environmental effects but also commercial and human losses. To solve this problem, the ship traffic in Istanbul Strait is managed with Traffic Separation Scheme (TSS). TSS was created by dividing the strait in half and directing ship traffic based on this reference line. However, the geographical structure and flow regime of the strait were not taken into account during the creation of TSS.

Data on marine accidents in the Istanbul Strait clearly show how important the current regime of the strait is for ship traffic. Between 2004 and 2017, 315 marine accidents occurred in the Istanbul Strait, and one of the most significant factors among the causes of these accidents was determined to be the two-way current flow regime existing in the strait[4]. The counterclockwise surface current around the North Anatolian Fault and the saltwater current from the Marmara Sea moving towards the other end of the strait make it difficult for ships to maneuver in their routes requiring sharp maneuvers[5]. Moreover, when this current flow regime combines with environmental and meteorological factors, marine accidents become inevitable. Therefore, solutions should be developed, taking into account the current flow regime factor, to prevent marine accidents in the Istanbul Strait.

Although ship traffic services (VTS) play a significant role in reducing marine accidents in the Istanbul Strait through determining and tracking ship routes, controlling ship speeds, maintaining distance between ships, and providing emergency response [6], they are not sufficient to prevent ship accidents caused by weakened maneuverability of ships against the current.

In this study, a risk analysis study based on ship bridge simulators was conducted to address the current regime of the Istanbul Strait and to propose the most suitable traffic separation scheme for the Istanbul Strait. The current flow pressure line-velocity change findings obtained through the potential flow theory from the literature were processed in simulator scenario packages and evaluated for different ship sizes. Thus, considering ship hydrodynamics, current flow regime, and maritime practice, the optimum TSS line was defined for certain ship size ranges for the first time in the literature.

II. Materials and Method

A. Potential Flow Theory

The potential flow theory is a method used to mathematically model the motion of fluids [6]. When studying the movement of fluids using potential flow theory, the viscosity of the fluid, i.e., the frictional force, and the energy losses that occur during the fluid's motion are not taken into account [7]. Thus, the theory models and analyzes the fluid's motion in a mathematically simpler way. This theory is particularly useful in various applications, such as underwater vehicles, ships, and airplanes, in the field of fluid dynamics [8]. The potential flow theory provides a basic understanding of the motion of fluids and forms a foundation for solving many complex problems [9].

Regarding the application of potential flow theory, there are different approaches depending on the problem in the literature. One of the most important approaches for modeling a current in a marine environment is the two-dimensional potential flow theory [10]. Two-dimensional potential flow theory studies two-dimensional motions and is based on the assumption that the fluid moves simply forward and backward without turning. This theory analyzes the fluid's motion using a potential function. The potential function is defined as the x and y components of the velocity vector at any point in the fluid expressed in terms of the x and y derivatives of the potential, respectively. The mathematical solutions of the potential flow provide important information about the fluid's velocity and pressure, helping to predict the behavior of the fluid. The two-dimensional potential flow theory is discussed by Suner and Bas (2022) using equations 1, 2, and 3 [10]:

$$F(z) = \varphi + i\psi \quad (1)$$

$$\bar{V} = u\bar{i} + v\bar{j} = \nabla\varphi = \frac{\theta\varphi}{\theta x}\bar{i} + \frac{\theta\varphi}{\theta y}\bar{j} + = \frac{\theta\psi}{\theta y}\bar{i} - \frac{\theta\psi}{\theta x}\bar{j} \quad (2)$$

$$\left|\bar{V}\right|^2 = u^2 + v^2 = p_1 + \frac{\rho}{2}\left|\bar{V_1}\right|^2 = p_2 + \frac{\rho}{2}\left|\bar{V_2}\right|^2 \quad (3)$$

If we assume $p_2 = p_0$, the following general equation can be written according to Bernoulli's theorem:

$$\left|\bar{V}\right|^2 = p_2 + \frac{\rho}{2}(\left|\bar{V_2}\right|^2 - \left|\bar{V_1}\right|^2)$$

B. Ship Bridge Simulators

Ship bridge simulators are an extremely important tool for research related to ship operations and maneuverability. Ship navigation, especially in narrow waters, ports, and congested waterways, is a complex process. Ship bridge simulators allow real-life scenarios encountered in ship operations and maneuverability to be modeled and simulated in advance, providing many benefits such as the training of ship personnel, improving ship navigation and maneuverability, reducing risk, and increasing environmental awareness [11].

A series of methodological approaches are recommended to create an ideal working environment in a bridge simulator:

i. Determine the purpose of the simulation: The first step is to determine the purpose of the simulation. This will help determine the required type of simulation, the necessary level of complexity, and the goals of the simulation.

ii. Define the simulation scenario: The simulation scenario should be defined based on the purpose of the simulation. This includes determining ship parameters, environmental conditions, and planned route.

iii. Execution of the prepared scenario: Based on the scenario, the execution of the scenario should be developed. This process includes the ship's response to environmental conditions and the interaction between the ship and its surroundings.

iv. Evaluation of the scenario package execution: After the simulation is completed, the results should be analyzed. This includes evaluating the performance of the ship, identifying any areas of concern, and determining necessary modifications or improvements.

v. Modification and re-run of the scenario: Based on the result analysis, modifications may be required. The scenario should be modified and re-run accordingly.

vi. Review of the simulation: The simulation should be reviewed and documented. This includes the purpose of the simulation, simulation scenario, ship parameters used, environmental conditions, simulation results, and any modifications made.

III. DISCUSSION AND CONCLUSIONS

In the literature review, it was observed that the current current models can successfully mathematically express the currents. The TSSs used in practice are usually created in a simple way, ignoring the currents and environmental dynamics. However, accidents and studies in the literature show that many current-related accidents can be prevented by updating the TSSs to include current and environmental variables with more detailed studies. Therefore, the use of a dynamic TSS instead of a static TSS would be more appropriate. Based on this, a current modeling was performed using potential flow theory for the area where accidents occur most frequently in the Istanbul Strait for the proposal of a dynamic TSS.

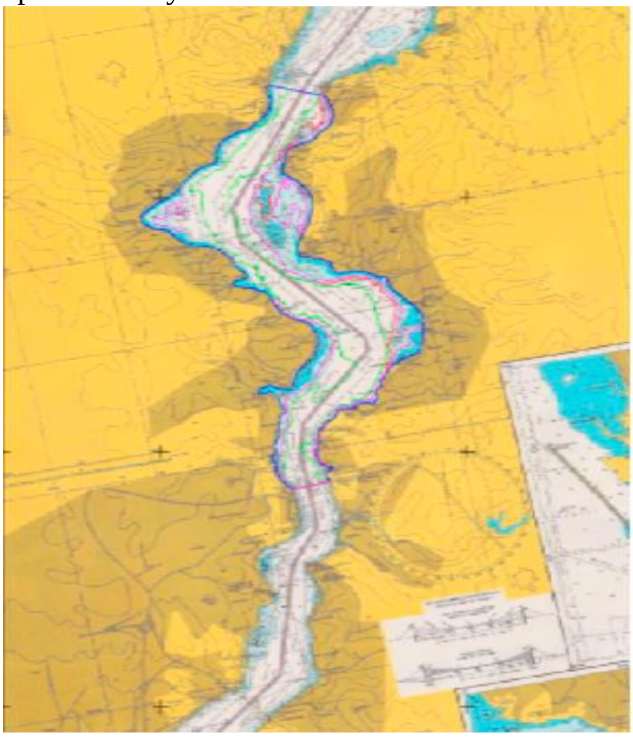

Figure 1: The area where marine accidents occur most frequently and where potential current theory and simulator studies are applied.

As mentioned in previous sections, the pressure contour obtained by Suner and Bas (2022) using the potential flow theory is as shown in Figure 2.

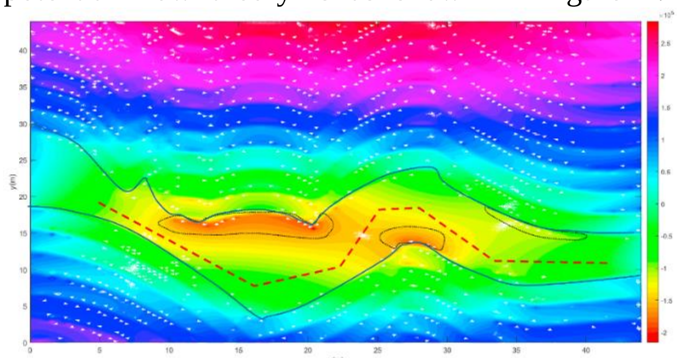

Figure 2. Neutral pressure line of the Istanbul Strait obtained by potential flow theory (Suner and Bas, 2022).

The green areas on the pressure line shown in Figure 2 indicate where the current is not very strong, while the yellow areas indicate where the current is beginning to increase in intensity, and the red areas indicate areas with serious navigation risks due to current intensity. Considering the current intensity, the authors proposed a TSS shown by the red dashed line. However, this proposed TSS determines the optimum line based on current intensity. Therefore, in order to obtain a better and more applicable TSS, these current velocity values (pressure values) were processed on a scenario package created on simulators.

In the application phase of the simulator study, passage through the Istanbul Strait was carried out on 10 different parallel routes with 4 different types (202000 dwt bulk carrier, 2100 TEU container ship, 19512 dwt lo-ro ship and VLCSS) of ships. In order to analyze the ships' resistance to currents at different speeds relative to the ground, these types of ships were selected for the simulator application and the ships were made to sail with full ahead, half ahead, slow ahead, and very slow ahead machine telegraph commands, respectively.

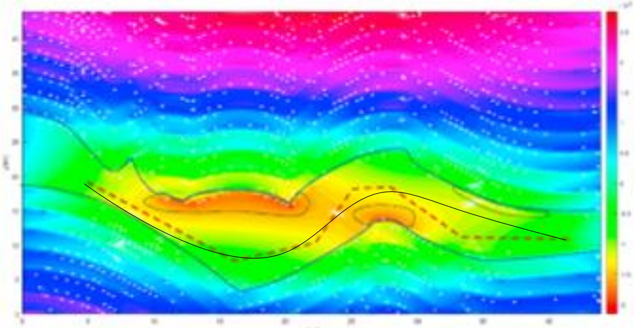

Figure 3: A hybrid potential flow theory and simulator base TSS recommendation for a selected area in Istanbul Strait.

Especially in low-speed ships with low velocity in areas where the current intensity increases, as in the potential flow theory findings given in Figure 2, it has been observed that the ships cannot overcome the current. However, due to the presence of components that cause unnecessary maneuvers, the inability of some ships to turn immediately, and the time required for maneuvering in the application of the TSS line shown with a broken line proposed by Suner and Bas (2022) according to the potential flow theory findings, a TSS proposal expressed in black colors in Figure 3 was put forward based on simulator-based experiments with four different ships. It was found that passing a little clearer from this line in low-speed ships and passing close to this line in high-speed ships would be safe under the impact on current. In addition, while there are 5 turning points-waypoints in the TSS proposed by Suner and Bas (2022) according to the potential flow theory findings (Figure 2), 3 turning points-waypoints (Figure 3) will be sufficient in this study. Accordingly, the limits of the optimum TSS line for the selected area in the Istanbul Strait are drawn as shown in Figure 3. The changes in risk depending on ship size on the TSS line with these boundary values obtained for 4 different ships of different sizes were also revealed.

IV. RESULTS

The strategic importance of the Istanbul Strait in world trade brings with it inevitable risks of accidents with thousands of ships passing through it every year. Therefore, the management of ship traffic within the TSS applied in the Strait is crucial. However, as in the rest of the world, the TSS is not designed considering the coastal structure and current regime, causing some ships to face the risk of accidents despite the TSS implementation, as they cannot overcome the current. In this study, based on the pressure-flow changes calculated cell by cell with the potential flow theory, optimum TSS proposals for the selected area in the Istanbul Strait have been presented using ship bridge simulators. The TSSs, determined by considering ship hydrodynamics, current regime and maritime practice, have been defined for specific ship size ranges for the first time in the literature. The research findings show that preventing accidents that may occur with a TSS, and making ship traffic safer, is possible by using a TSS designed according to ship sizes and coastal structures.

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