NAVIGATION SUPPORT SYSTEM FOR NARROW WATERWAYS, A CASE STUDY: STRAIT OF ISTANBUL

Mustafa Anil Yazici[1], Emre N. Otay[2]

ABSTRACT

A real time traffic control tool was developed for safe route navigation of vessels in the Strait of Istanbul. Using channel geometry, bathymetry, counter traffic, and surface currents as input, the model simulates possible maneuvers according to probable hydrodynamic conditions. The decision making algorithm starts after computing the probable trajectory tree of the vessel by forward-mapping its position distribution with respect to an initial position vector. The proposed software tool uses an experimentally verified container ship model and a proportional-derivative (PD) auto-pilot to represent the captain's response. Two different algorithms are used for cases with and without clear and present collision risk. For both cases, the route with minimum casualty risk is found. In case of multiple "quasi-risky" routes, some safety based tie-breaker criteria are taken into account. Within certain restrictions on vessel geometry, the proposed tool predicts the safest route for transit vessels in the Strait based on the navigational parameters including position, speed, and course of the vessel. Proposed model can be used for any narrow channel with a vessel traffic system providing the necessary input.

KEY WORDS

Strait of Istanbul, Navigation, Simulation, Decision Making, Safety

INTRODUCTION

The Strait of Istanbul (also known as the Bosporus) is a narrow waterway accommodating an annual traffic of approximately 50,000 vessels carrying various types of cargo including hazardous and explosive materials. The Turkish government has implemented a $30 million Vessel Traffic System (VTS) to improve navigational safety in the Turkish Straits. The VTS operators track transit vessels in the Strait and only warn the captain if a dangerous activity is detected. However, there is no decision support system for the VTS (although legal aspects of this issue are further complicated) to determine the safest route in case of an emergency or unsafe navigation. This study proposes an algorithm to be used with the existing VTS system, as well as applicable to any narrow channel with a system providing the necessary input.

The paper outline is as follows. First, a literature survey is presented, followed by the physical characteristics and the vessel traffic of the Strait. Then, the ship hydrodynamics, the auto-pilot module and the decision making model are discussed in detail. Finally a

[1] Grad. Asst., Civ.& Env. Engrg. Dept., 623 Bowser Rd., Rutgers Univ., Piscataway, NJ, 08854, USA, Ph. +1(732)445-5496; Fax +1(732)445-0577. yazici@eden.rutgers.edu

[2] Assoc.Prof., Civ.Engrg.Dept., Bogazici Univ., Bebek, 34342, Istanbul , Turkey, Ph. +90(212)359-6432, Fax +90(212)287-2457; otay@boun.edu.tr

model validation for testing the proposed algorithm and some conclusive remarks about the model are presented.

PAST WORK

Kornhauser and Clark (1995) exploit a regression model prepared by the United States Department of Transportation for the U.S. Coast Guard's Office of Navigation Safety and Waterway Services to forecast the number of casualties in the Strait of Istanbul. The model ignores time variations in the distributions of vessel sizes and arrival rates. Instead, it only incorporates past data such as the past casualties, channel width, average current velocity, wind velocity, visibility etc. It also assumes that the casualty rate is independent of the volume of traffic and therefore tends to underestimate the number of casualties that result from the increase of oil tanker traffic. Tan and Otay (1999) propose a physics-based model for determination of spatial risk distribution in narrow channels. Markov chain analysis is performed with the help of state space representations of vessel positions. Their outcome coincides with the results of Brito (2000), who approaches the congestion of vessel traffic in the Strait of Istanbul from an economic and political perspective with a Markov chain model. Both studies ends up with the result that there is a quadratic relation between the volume of the traffic and the casualty risk. Ozkan (2003) investigates the spatial distribution of the grounding and the collision probabilities in the Strait of Istanbul incorporating a CFD based ship navigation model, focusing on pilotage behavior and errors. In his work, the pilotage is treated as a stochastic process, which causes an uncertainty in the ship maneuvering for given surface current conditions. The position distributions, which are the result of the pilotage differences, are used to find the casualty probabilities. The high casualty risk regions found through the model match with the real life data but the number of casualty forecasts regarding the calculated probabilities does not represent the reality. Yazici (2004) proposes a real time traffic control model for narrow waterways and applies the model to the Strait of Istanbul for validation. The model is claimed to work satisfactorily, and risk measures are introduced to check the performance of implemented navigation policies for the Strait of Istanbul. Kahraman (1999) and Gören (2002) investigate the Bosporus by data regression and statistical simulations and propose descriptive models for the safety of the Strait. Sariöz *et al.* (1999) perform a real time ship maneuvering simulation investigating the performance of large tankers in the Strait. The paper verifies the present regulations' assumption that ships longer than 200 m cannot keep within the traffic lanes safely, even in no current conditions. The smaller ships are capable of keeping within the traffic lanes, however, this finding depends on pilotage skills.

STRAIT OF ISTANBUL

The Strait of Istanbul is one of the most difficult channels in the world to navigate due to its geometry with sharp and narrow turns as well as its vulnerability to environmental effects. The Strait is about 31 km long and 700 m – 3500 m wide, the narrowest section being 671m. Water depths in the navigation channel varies around a mean of 33 m with a maximum depth of 110m (Özkan, 2003). To navigate the curves, vessels have to change their courses at least 12 times with a maximum angle of 80 degrees. Researches dating back to 16th century (Count Marzignly) show that the Strait has a two layer flow. The water in the upper layer flows from the Black Sea to the South driven by elevation and

salinity differences. On the other hand, the water in the lower layer flows in the opposite direction (from Marmara Sea to the Black Sea). The current magnitudes vary up to %40 in an hour (Bosporus Railroad Tunnel Hydrographic Survey, 1987). Although these measurements were conducted in the lower layer, the reported standard deviation for the velocity fluctuations are used for the surface currents in the present study due to the lack of more comprehensive field data.

VESSEL TRAFFIC IN THE STRAIT

The annual passage rate in the Strait is about 50,000, which corresponds to 135 vessels per day. Projections indicate an increasing trend exposing increasing risk on City of Istanbul because approximately 10% of the navigating vessels carry hazardous liquid cargo. The vessels passing through the Strait have varying lengths. More than 50% of the ships are between 50-100 m and the percentage decreases for longer ships. About 4% of the vessels are longer than 200m. As Sariöz *et al.* (1999) state, ships more than 200 m cannot keep the required lanes proposed by the traffic separation scheme even in no current condition.

Traffic Separation Scheme (TSS), which basically divides the channel into lanes, was put in action on July 1st, 1994 with the approval of International Maritime Organization (IMO). In 2003, a Vessel Traffic System (VTS) was implemented for continuous tracking of navigating vessels in the Strait and checking the vessels to keep up with the lanes. Ships longer than 200m are not allowed to enter the Strait in opposite directions. For ships longer than 300 m, all other traffic in the Strait is suspended to ensure safe passage.

SHIP HYDRODYNAMICS

Modeling of ship movement and maneuvering is an important part of this work because this study is aimed to have a physical basis rather than being a statictical analysis. However, ship hydrodynamics is a complicated subject not only related to ship geometry, but also rudder and propulsion dynamics. Solution of the governing equations is computationally intensive and nonlinear in nature. Thus for a reasonable run time, the solver needs semi empirical constants (like hydrodynamic derivatives) obtained from scale tests. For this study, the four-degrees of freedom (DOF) container ship model in the MATLAB Marine Cybernetics toolbox developed by Thor I. Fossen (Marine Cybernetics, 2001) is used. The standard six-DOF representation with standard notation and sign conventions for ship motion can be seen in Figure 1.

Hydrodynamic modeling is based on a state-space representation which gives the model flexibility to introduce other forcing mechanisms easily. This flexibilty was used to introduce stochastic drift forces. Response constants of auto-pilot module given in the toolbox was tuned to have a sufficient maneuvering performance for narrow channel navigation. The current force that causes drift in vessel route is calculated with the formula:

$$\vec{F}_{Dsway} = \frac{C_D D}{2LU^2}\left|\vec{V}_{cy} - \vec{v}\right|\left(\vec{V}_{cy} - \vec{v}\right)$$

where C_D is the drag coefficient, D is the ship draft, L is the length of the ship, U is the speed of the ship, $\vec{V}_{cy}$ is the current velovity projected into ships's sway direction, and $\vec{v}$ is the velocity of the ship in sway direction.

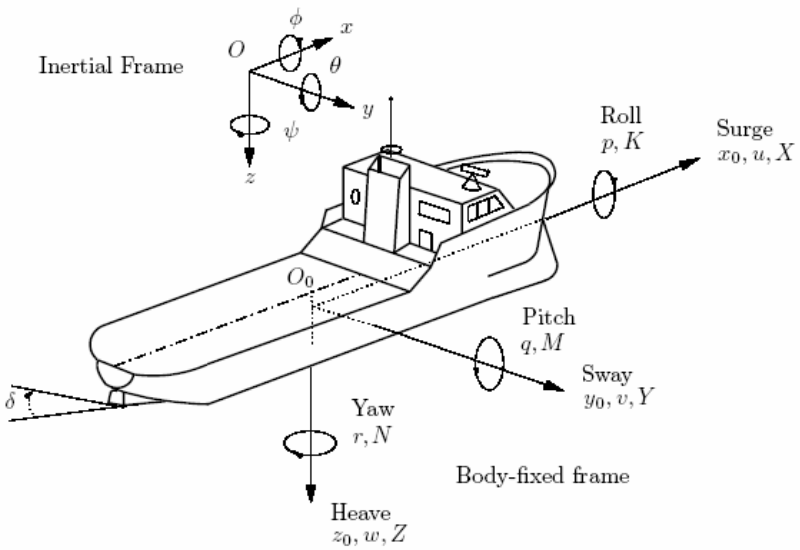

Figure 1 Standard notation and sign conventions for ship motion description (Perez and Blanke, 2000)

DECISION MAKING MODEL

The main target of the decision algorithm is to span the strait geometry by possible route trajectories under predetermined heading angles and probabilistic surface currents, so that the safest route can be chosen among the possible ones. Here, the term safe refers to common public good where the route trajectories will be chosen not to endanger the public in all sense, including the ship owner and personnel. Neither grounding is completely preferred to prevent collision of ships, nor is collision desired to protect the coastal structures along the Strait. The model proposes some spatial constants to be adjusted according to the type of casualty preferred to happen in case of an unavoidable incident, but all kinds of casualty is considered undesirable during all the decision making process.

The model has some variable physical input parameters such as ship characteristics, vessel position and the surface currents. Those inputs are updated continuously along the Strait to compute the real-time trajectory projections. Only the ship length and draft are constant during the simulation, where navigational parameters like vessel speed, yaw angle, and surface currents are subject to change during navigation.

The stochastic variables in the analysis are the surface current magnitudes. The surface currents are assumed to have a distribution with a specified mean and variance. Desired heading is accepted to be the angle between the Strait centerline and North, which is basically the mean alignment of the Strait. Vessels navigating close to the desired heading are assumed to navigate safely. The possible heading angles that are simulated are found through adding and subtracting small predetermined deviations from the desired heading. In fact, possible headings can be given to cover a wide range but it is

obvious that the diverged values will not be reasonable for narrow channel navigation. This intuition saves time for the computation. After determination of possible headings, the navigation simulation is performed for each heading. Each heading value forms a route from the chosen initial point. In every simulation, the current forces are updated by incorporating different current magnitudes to obtain different route trajectories for a fixed heading. All trajectories are assigned probabilities according to the associated current characteristics that will result in that trajectory. The final trajectories are stored with corresponding probability distributions to be used as the position distributions for the selected heading.

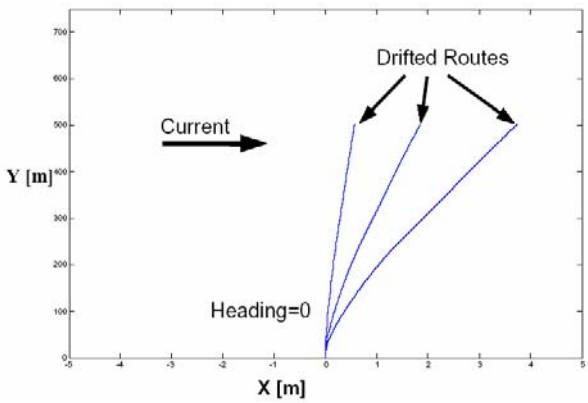

Figure 2 Illustration of Vessel Drift with Changing Current Magnitudes

The mathematical model is based on a dynamic, time dependent analysis where the simulation is re-performed several times during the vessel passage. This dynamic property creates flexibility to respond to the changes in speed or any deviation from the proposed safe route. The simulation is performed for a fixed time interval and all the data regarding possible trajectories including ship velocity, spatial position, yaw angle etc. are stored. The line where all the position parameters are stored is said to be the check line. The check lines are assigned dynamically according to the ship's speed, coordinates and the channel geometry. Some checklines are forced by the program at places where the vessels need to change their courses or they can be set by the program operator according to the time interval between two consecutive analyses. The main idea of the checklines is to employ them as a reference point for further projections and to check if the vessels follow the proposed route. The simulation is performed in a consecutive manner, in which the distributions are mapped onto the following check line. New trajectories are found by taking each stored final position as an initial point for the next simulation. The current that is experienced at two consecutive simulations are accepted to be independent meaning that an occurrence of a current pattern does not affect the next pattern for the analysis. The resulting trajectory tree can be expanded until it is sufficient to support a rational decision. In case of the Strait, the trajectory tree is expanded until it covers a 1 km long range per simulation. If the 30 km length of the Strait is taken into account, 1 km range can be accepted as "sufficiently rational".

In general, the vessel is assumed to follow the proposed safe route and the vessel is tracked at relatively small time intervals. In every simulation the proposed trajectory is updated according to the updated data obtained from the vessels and the navigation

control system. The main idea is to be able to propose a new safe route for any circumstance that may happen, provided that enough data is available to feed the simulation.

After all the position distributions for the routes are found, a post-processing unit uses the obtained distributions to calculate the grounding and collision probabilities for each route (Figure 3). The area under the position distribution, which falls on land, is used to calculate the grounding probability and the area under the intersection of two ships navigating in opposite directions is defined to be the collision probability. When the distance between two vessels are more than pre-assigned $d_{critical}$, which means that there is no collision risk in near future, the decision making algorithm takes only the grounding into account. When the vessels are close according to $d_{critical}$, algorithm uses both the collision and the grounding probabilities and proposes the safe route accordingly.

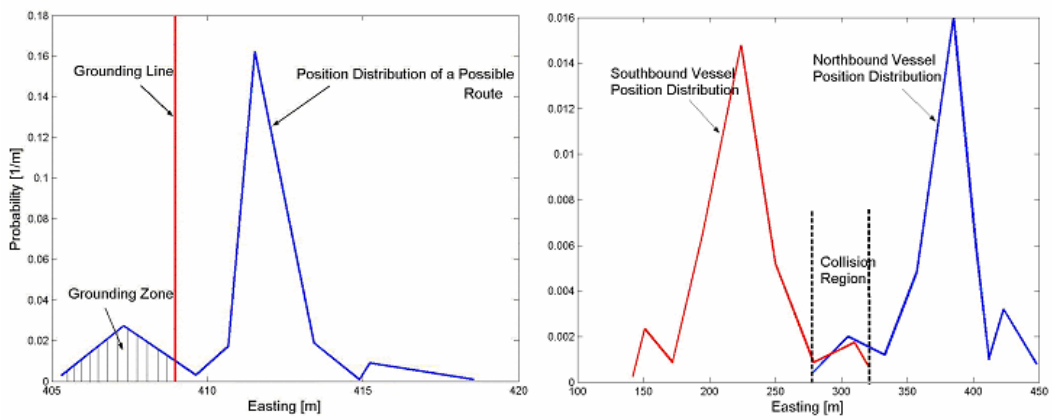

Figure 3 Calculation of Grounding and Collision Probabilities

The most crucial variable of the simulation is the surface current. All the analysis is based on the fact that fluctuations in the current magnitudes will cause deviations from the ship's course. In this study, the data measured in 27.11.2002 by Turkish Navy Department of Navigation, Hydrography and Oceanography is used. In the analysis, the probaility distribution of the surface current magnitude is dicretized at fixed number of points using the associated probability.

Route Assignment

Figure 4 shows the probability assignments for the drifted routes. Here P_{ij} stands for the drift probability where *i* gives information about the spatial coordinates of the region where the route lies and *j* gives the information about the current that drives the vessel to the stated point. The total probability of a drifted route is the subjective probability where the route is assumed to be on a specified position with a given probability, say P_{12}. All the routes emanating from that point is multiplied with this value, e.g. if the trajectory following drifted route 1-2 is drifted by a current magnitude with probability P_{21}, then the probability that the vessel will end at drifted route 2-1 is $P_{12} * P_{21}$. Here, the assumption that "the surface current magnitudes at consecutive regions are independent" is employed for calculating the probabilities.

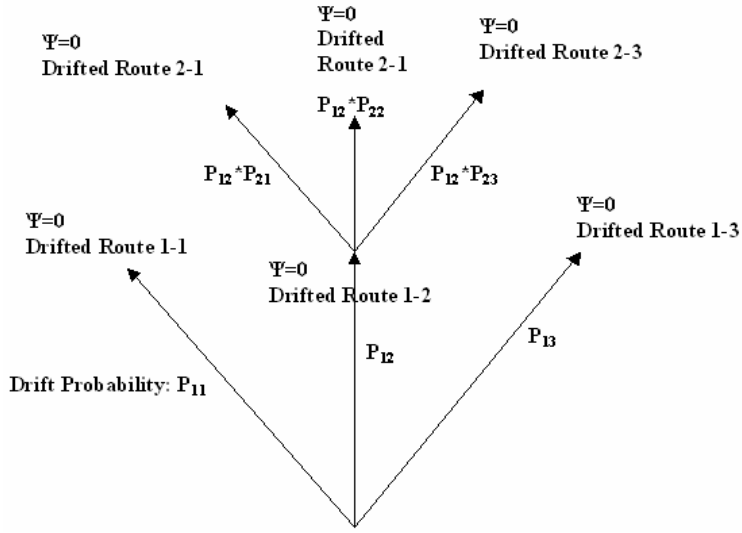

Figure 4 A sketch of route probability assignments

Decision Making Algorithm

Decision-making algorithm constitutes the final output of the model and works as a post-processing module. The output of the trajectory simulations is processed to propose the best one among them. There are two subroutines of decision-making process written for 2 different casualty threats. At the beginning of the analysis, if the distance between the two ships navigating in opposite directions is over a threshold (which is presently set to 2000 m), the "Grounding Only" algorithm is employed. However, if the distance is below the threshold, the "Collision Combined" algorithm, which takes the collision probabilities into account, is used for the analysis. "Collision Combined" algorithm includes two coefficients named α and β representing the weight of collision and grounding probabilities in the decision process, respectively. These coefficients give the program flexibility for stating the priority of casualty type that is preferred to the other one, e.g. increasing collision coefficient α if grounding is preferred to collision for that section of the channel.

Although the two algorithms are different from each other, they have some common aspects for decision. For example, both of them use the same logic for selecting the optimal route from "quasi-risky" routes. Quasi-risky term is introduced because sometimes two routes may not be distinguishable according to their probabilities. Two trajectories with same probabilities, which mean that they are within a certain interval, say ε, are assumed to be "quasi-risky" and they are assigned to be the optimal candidates. That's why most of the time there are more than one optimal route. In those cases both algorithms use the criteria explained below, to select among the quasi-risky routes.

- The routes with heading equal or close to the longitudinal orientation of the channel is preferred.
- If the above constraint is satisfied by more than one route, the route with minimum number of heading alterations is chosen.

- If there is still more than one candidate, the route with end point having greatest distance from the channel borders is selected.

Priority of those criteria change in "grounding only" and "collision combined" algorithms, and the differences will be discussed in the proceeding sections.

"Grounding Only" Route Optimization

Grounding algorithm only processes the grounding possibilities for decision.

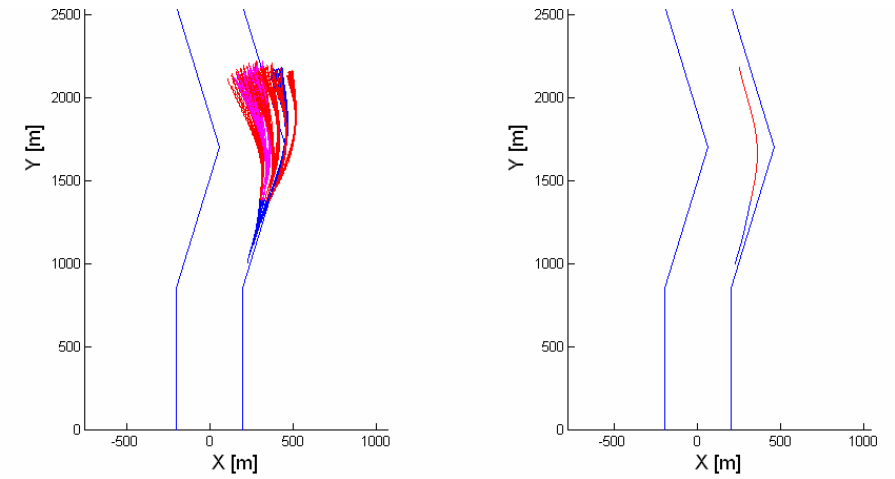

Figure 5 An Illustration of Safe Route Selection with Grounding Only Algorithm

Figure 5 can give a summarizing idea about the grounding only route selection. There seem to be better routes which are further away from the borders than the optimum route, however if a vessel is to follow one of these routes, it will have a different yaw angle at the end. This will make it much harder to adjust the vessel for the next corner, because the vessel has to make a sharp move to be able to complete its maneuver at the next turn. The algorithm eliminates the routes with undesired yaw angle. Nevertheless if it turns out that there is no such route with the desired yaw angle than the algorithm uses the tiebreaker rules for the final decision.

"Collision Combined" Optimization

Collision combined optimization differs from the grounding only algorithm by avoiding collision as well as grounding. This mode is switched only when two vessels are close enough to alarm a collision probability. This distance is set to 2000m, which is little more than 3 minutes of navigation time before collision. To avoid collision, the respective maneuvers of both ships are important. One vessel can avoid the other easily by maneuvering to the other direction of the opposite-navigating vessel, however this may cause grounding. Collision combined algorithm deals with this problem by keeping the legal navigation rules in mind.

Collision probability is determined by the area under the probability curves of position distributions for the two oppositely navigating ships and it is dependent on maneuver pairs

chosen by both the northbound and the southbound vessels. To determine the total casualty probability of the chosen route pairs, the individual grounding probabilities of the chosen routes are considered as well as the collision probability.

After defining the total casualty probability for every route, similar procedure to grounding optimization is employed. A matrix is formed such that the northbound casualty probabilities are in its rows and the southbound casualty probabilities are in its columns. The matrix values represent the total casualty probabilities of the respective maneuver pairs. First, the minimum probability is found and all the route combinations are analyzed according to this minimum value. The route combinations that have a close risk value (within 10^{-3}) are chosen to be "quasi-risky". Then, for every northbound route, the possible quasi-risky routes are kept and the others are eliminated. Afterwards, the southbound routes are given a priority according to the tiebreaker criteria with one adjustment. The grounding only algorithm performs the second elimination according to the minimum maneuver numbers where collision combined algorithm uses the projected distance between the ships for elimination. This is mainly due to an uncertain situation of two vessels navigating close to each other. The ship handling failure probabilities and breakdown possibilities increase with increased number of vessels, thus algorithm tries to set them apart from each other. The same procedure is applied to northbound routes and the elimination according to the desired heading is performed. The order of elimination is just a matter of choice and do not affect the overall decision result.

The decision of route combinations cannot be purely mathematical, like minimizing or maximizing the distance, but rather include legal navigation aspects. According to international regulations for preventing collisions at sea, the ships must maneuver to starboard side to avoid collision. So the decision process includes this aspect as a constraint and the proposed route combinations are chosen according to legal regulations. The maneuver number is taken into account when there is more than one combination with the same casualty outcome. The outcome of the decision-combined algorithm is a pair of routes proposed for both the northbound and the southbound vessels given according to both mathematical concepts and navigation regulations.

Figure 6 illustrates a condition where two vessels approach each other, and southbound vessel is navigating on the wrong lane. Both vessels are proposed a starboard maneuver for a safe passage (Figure 6, left hand side). Key point in this representation is that the algorithm takes into account the navigation rules and physical conditions at the same time. The proposed safest route is based on legal rules (starboard maneuver) if it is possible, but if the positions of two vessels are apart from each other so that starboard maneuver cannot be performed safely, then the algorithm proposes a port maneuver (Figure 6, right hand side).

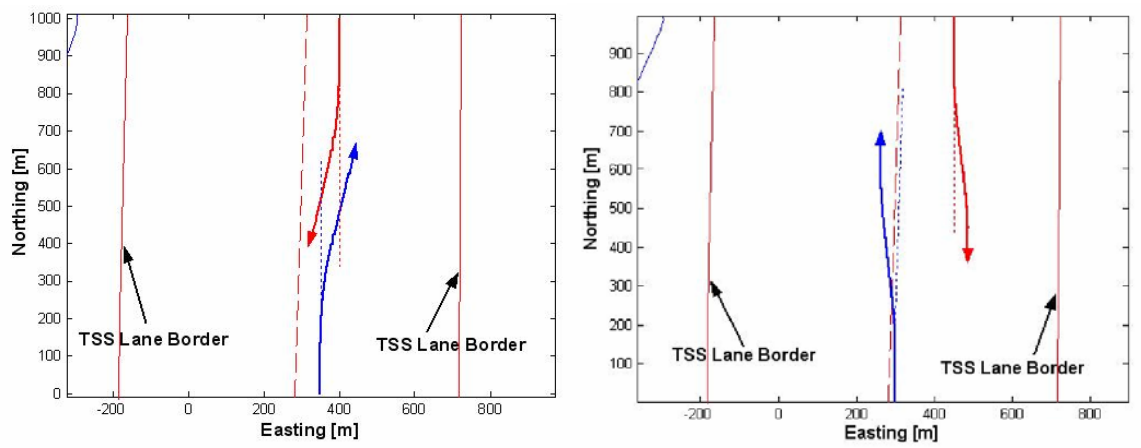

Figure 6 An Illustration of Safe Route Selection with Collision Combined Algorithm

CONCLUSION

The model proposed in this study yields promising results in terms of proposing safe routes in a narrow channel navigation. Two algorithms, namely ”Grounding Only” and ”Collision Combined”, are tested for various scenarios and they manage to propose reasonably safe routes for the navigating vessels. However, some limitations still exist. The most important limitation is that the vessel geometry changes cannot be accomodated since there are not many vessel models available. Also current measurements need more details for a more reliable analysis. Nevertheless, the proposed model works in modules, thus any improvement on either aforementioned limitations can be incorporated into the model without much difficulty. Nevertheless, the legal issues for captain’s obligation to follow the model propositions and reliability problem of the proposed route stay still as an obstacle for the real life implementation of the model.

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