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Traffic Safety Analysis in Mombasa Channel: Integrating Ferry Crossings and Main Transit

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Abstract : *This study examined challenges posed by two ferry routes, namely, Likoni and Mtongwe crossings, in the Mombasa Channel and their impact on navigational safety. Utilizing the Environmental Stress (ES) model, this study analyzed current ship traffic and assessed stress levels imposed by ferry crossing traffic on navigators. ES values revealed significant stress at these ferry crossings attributed to varying transit speeds. Standardizing transit speeds at two ferry passages can reduce high stress levels, presenting a viable solution. Furthermore, the IWRAP Mk2 simulation underscores crossing collisions as a significant concern, particularly at Likoni and Mtongwe crossings, due to increased ferry traffic. This research offers valuable insights for stakeholders, such as the Kenya Ports Authority (KPA), to develop targeted safety measures and enhance the flow of ship traffic in the channel.*

Key words : *risk assessment, Mombasa Channel, Environmental Stress (ES) model, IWRAP Mk2, AIS data, ferry crossing, transit traffic*

1. Introduction

Mombasa Channel is situated at coordinates 4° 03′ S latitude and 39° 39′ E longitude within the coastal city of Mombasa located in the Republic of Kenya (Kenya Ports Authority, 2024a). The waterway serves as a vital artery for the Port of Mombasa, the largest maritime port catering to Kenya and a broad swath of East and Central African nations, including Uganda, Tanzania, Burundi, Rwanda, Somalia, Sudan, and the eastern part of the Democratic Republic of the Congo (Ngangaji, 2019). This waterway is marked by bustling maritime activity, featuring two local ferry routes and a transit traffic flow for vessels navigating to the port's berths.

The two ferry pathways facilitate the daily movement of 150,000 pedestrians and 5,800 vehicles. The Kenya Ports Authority (KPA), a state corporation, is charged with the management of ferry operations within the Mombasa Channel. Its Ferry Operation department is responsible for transporting passengers, motorists, and cargo through these two transits with a fleet of seven ferries(Kenya Ports Authority, 2024b).

In August 2019, a critical incident nearly occurred in the Mombasa Channel: a heavily loaded ferry at Likoni passage almost collided with an oil tanker navigating the ferry crossing zone. The tanker, en route to Kilindini harbor, came perilously close to the ferry, highlighting a significant risk (The Standard, 2019). The potential consequences of such a collision were dire, including the possibility of massive loss of life and severe environmental damage, particularly oil pollution affecting coral reefs and marine ecosystems (Mwaguni et al., 2013). This incident underscores the urgent necessity for stringent management of ship speeds at the two ferry crossings. Implementing standardized speed limits for all vessels traversing these zones emerges as a critical measure to enhance safety and prevent future near-miss incidents or actual collisions.

This research utilizes the ES simulation model alongside the IWRAP Mk2 model to meticulously assess the navigation risks posed to maritime traffic within the Mombasa Channel, specifically focusing on the interactions between local ferry operations and main transit movements. Leveraging third-party Automatic Identification System (AIS) data spanning from October 10th to October 17th, 2022, the study provides a comprehensive analysis of the navigational pressures and potential collision risks faced by vessels in this busy waterway. Through detailed examination of stress levels experienced by navigators and the probability of collisions, the research aims to contribute significantly towards the improvement of maritime safety

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measures and the development of robust navigation protocols, benefiting both the ferry services and the broader maritime traffic in the Mombasa Channel. The flow of the research is shown in Fig. 1.

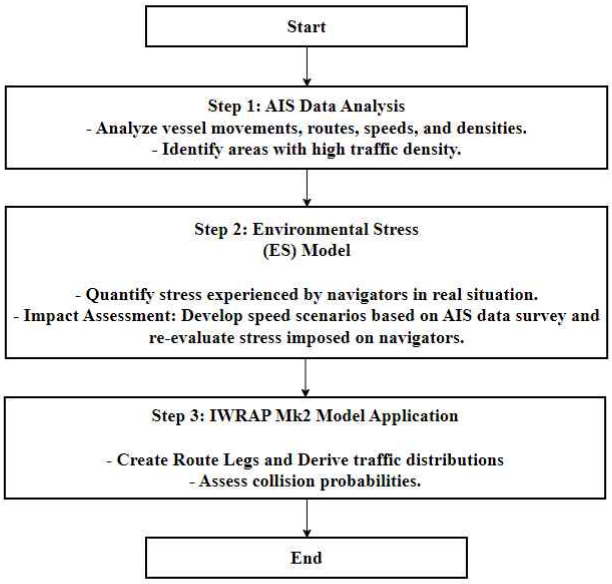

Fig. 1 Research flow

2. Literature Review

Maritime traffic risk assessment is a multidisciplinary field aiming to quantify safety levels in navigational areas. Researchers such as Zhen et al. (2017) have emphasized its importance, highlighting three primary categories of methodologies employed in this domain.

Firstly, statistical methods, as applied by Kujala et al. (2009), involve the analysis of accident data to identify patterns, trends, and risk factors contributing to maritime incidents. These methods rely on historical data to develop probabilistic models and estimate the likelihood of accidents occurring in specific maritime environments.

Secondly, the assessment of non-accident data, as explored by Szłapczyński (2010), involves analyzing ship trajectories and other relevant information over time to predict safety levels in waterways. By examining factors such as vessel movements, traffic density, and interaction patterns, this approach aims to identify potential risk areas and assess the overall safety of navigation routes.

Lastly, risk modeling based on simulation models, exemplified by the ES model and IWRAP Mk2 models, integrates computational simulation techniques to assess maritime traffic safety.

The ES model facilitates the simulation of various scenarios, events, and interactions within a maritime environment, allowing for a detailed assessment of potential risks and their impact on the navigators' stress levels due to ship handling difficulty in the presence of other vessels. Notably, the ES model's risk acceptance criteria was developed from subjective judgments as provided by Japanese navigators as a result of ship handling simulators and questionnaire-based evaluations. The ES model stands out for incorporating human factor input into its risk acceptance criteria, a dimension often overlooked in existing maritime traffic risk assessment techniques. On the other hand, the IWRAP Mk2 program incorporates factors such as vessel and traffic distribution characteristics and causation probabilities to evaluate overall safety levels in waterways. Kim et al. (2011) applied both the IWRAP Mk2 program and ES model to evaluate maritime traffic safety in the Ulsan waterway, South Korea. Their study found that while both models provided valuable insights, the ES model offered a more comprehensive evaluation of risk consciousness among navigators.

ES and IWRAP Mk2 models can be utilized by researchers to identify critical safety issues in waterways and develop targeted risk mitigation strategies. This combined approach combines statistical analysis of ship data, human factors and computational modeling to improve maritime safety and navigation efficiency.

3. Methodology

3.1 AIS Data Analysis

The analysis and visual representation of AIS data, capturing the movements of vessels through the Mombasa Channel over a week in October 2022, were essential. This data, depicted in Fig. 2, provides a crucial snapshot of maritime activity, offering insights into traffic patterns of transit traffic and the two crossing ferries, vessel behaviors, and potential navigational challenges within this critical waterway.

The ferries navigating Mombasa Channel utilize two primary crossings, namely, Likoni crossing and Mtongwe transit.

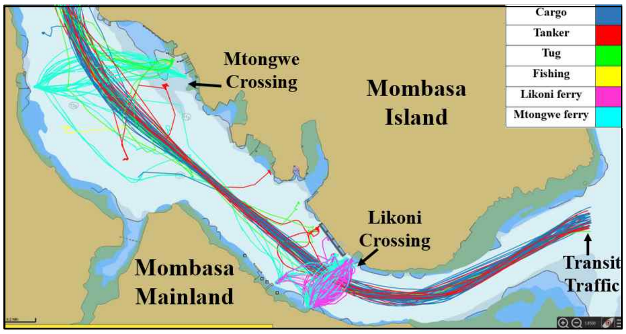

Fig. 2 Traffic flows in mombasa channel from 7 days AIS data for underway vessels

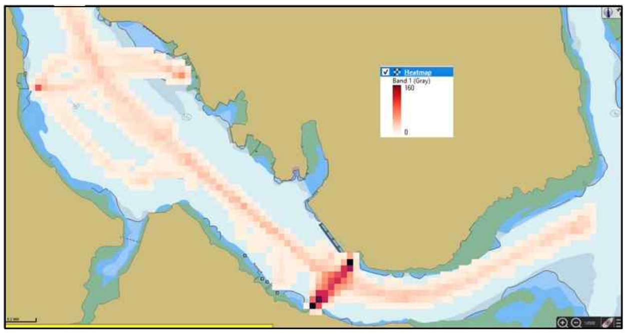

Fig. 3 Traffic density using kernel density estimation

The Likoni passage spans approximately 500 meters in width in contrast to the Mtongwe crossing which extends about 1200 meters. Likoni crossing features the highest frequency of ferry crossings in comparison to the Mtongwe route, with the AIS data for the selected period indicating the presence of only one ship per crossing. Specifically, the Likoni passage can experience up to four ferry crossings per hour, with vessels reaching maximum speeds of up to 5.3 knots. In contrast, the Mtongwe crossing exhibits a lower crossing frequency, with a maximum of two crossings per hour as recorded in the AIS data survey. The fastest speed noted at Mtongwe crossing was 5 knots, underscoring a variance in operational dynamics between the two ferry routes.

The analysis of underway ship traffic density from the AIS data employed the Kernel Density Estimation (KDE) method, a technique proven effective by Willems et al. (2013) for mapping out ship density and identifying key navigational features, such as anchor areas and sea lanes. This approach revealed that the Likoni crossing experiences higher vessel concentrations compared to other segments within the study area, indicating it as a critical focal point for maritime traffic assessment. The spatial distribution of this traffic density, highlighting areas of heightened navigational activity, is detailed in Fig. 3, offering insights into the complexity of ship movements and the necessity for targeted management strategies at this busy crossing.

3.2 Environmental Stress (ES) Model Analysis

The ES simulation model, developed by Inoue (2000), serves as a quantitative tool for evaluating the stress imposed on the navigators when handling ships within narrow and busy waterways. It plays a crucial role in analyzing the complexities of ship maneuvering in areas plagued by geographical limitations or significant vessel congestion. This research specifically addresses the ship-handing challenges presented by the maritime traffic conditions in the Mombasa Channel, quantifying navigational stress—denoted as Environmental Stress imposed on the mariner due to other Ships (ESS)—based on the proximity and potential collision paths with other vessels, thereby offering insight into the safety measures needed to protect both local and transit maritime operations.

3.2.1 Risk Analysis for Original Scenario (Current Situation) Utilizing the ES Model

An ES simulation model risk assessment scenario was employed to analyze the current maritime traffic conditions in the Mombasa Channel, based on AIS data. This assessment's traffic flow designations are detailed in Fig. 4, providing a foundation understanding of the navigational dynamics within the channel.

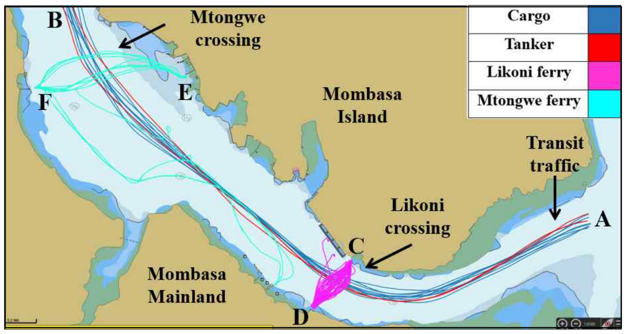

Fig. 4 Traffic flow designations

Using AIS data, two ferries at the Likoni and Mtongwe crossings were identified for analysis in Crossing Cases 0-1. Additionally, seven simulation cases (Cases 2-8) were constructed to examine the impact of varying maximum speeds on transit vessels, including cargo ships and tankers that constitute the main transit flow. The specifics of these cases, reflecting the diverse maximum speed scenarios under consideration, are outlined in Table 1.

Table 1 ES model input parameters

Simulation Cases	Traffic Flow ID	L.O.A. (meters)	Maximum Speed (knots)	Traffic Volume (ship(s)/hour)
Case 0	C to D; D to C	85.0	5.3	4
Case 1	E to F; F to E	75.0	5.0	2
Case 2	A to B	244.0	11.7	1
Case 3	A to B	223.0	8.55	1
Case 4	A to B	225.0	9.7	1
Case 5	A to B	200.0	7.1	1
Case 6	A to B	270.35	12.75	1
Case 7	A to B	222.16	14.1	1
Case 8	A to B	177.0	10.0	1

After devising the simulation scenarios and integrating them into the simulation code, the code was executed, resulting in the generation of traffic flows, as depicted in the Fig. 5. Within the figure, the traffic viewer illustrates a collision scenario involving the crossing Likoni ferry and ta transit vessel, as observed in the simulation output.

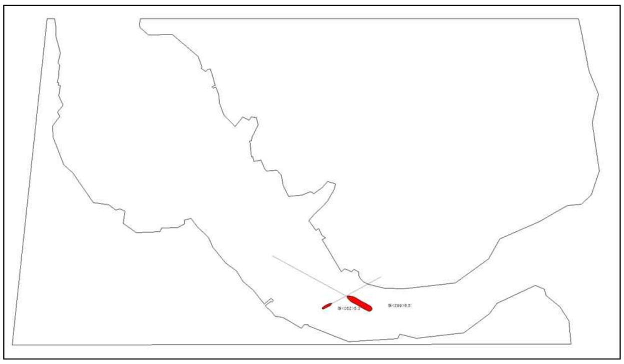

Fig. 5 Traffic flow visualizer for ES model output

3.3 IWRAP Mk2 Analysis

The IALA Waterway Risk Assessment Program (IWRAP Mk2) is a simulation tool that is applied for maritime risk assessment. This tool is utilized in evaluating the probabilities of collision, grounding and allision accidents in a particular waterway based on input data such as traffic volume, ship route geometry and bathymetry(IWRAP, 2023). Using AIS data as the input data for the program, collision probabilities were generated to assess the maritime traffic risk in the channel.

3.3.1 Creation of Route Legs

When defining the model of Mombasa channel, the route legs were created and adjusted based on AIS data as illustrated in Fig. 6. The Leg Tool from the software's toolbar was used to create the route legs and waypoints. The traffic routes consist of a sequence of way-points linked by the route legs. Each leg specifies the distribution of vessels in terms of size and type, as well as their dispersion.

Fig. 6 Route legs in mombasa channel

3.3.2 Traffic Distribution

After defining each leg, the probability distribution of the traffic dispersed along the route was established for each leg as illustrated in Fig. 7.

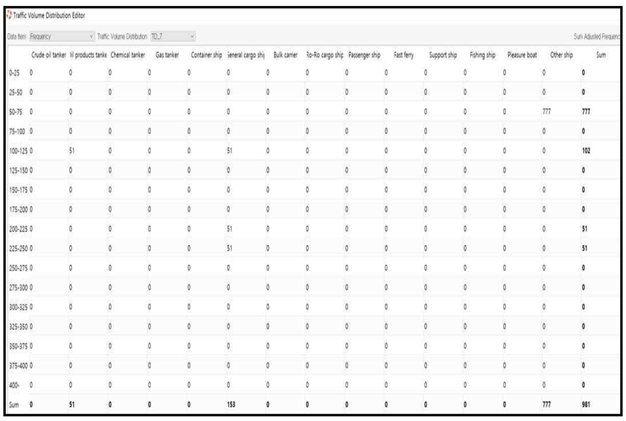

Fig. 7 Traffic volume distribution in IWRAP Mk2 software

In addition, the standard deviation for each route leg was defined as shown in Fig. 8. for both the north bound and south bound ships.

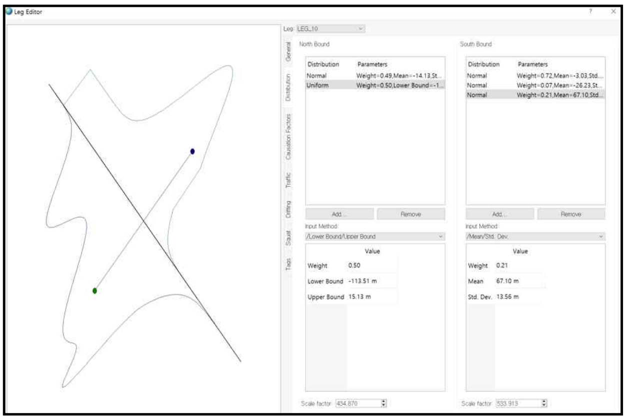

Fig. 8 Route leg information in IWRAP Mk2 software

4. Results and Discussion

4.1 ES Simulation Model

The simulation's outcomes, specifically the total ESS values, were visualized using QGIS software, as depicted in Fig. 9. In this visualization, green tracks represent ESS values under or equal to 500, denoting negligible stress, while yellow tracks indicate ESS values between 501 to 750, considered marginal. Orange tracks portray ESS values between 751 to 900, categorized as critical, and red tracks signify ESS values of 901 and above, highlighting areas of catastrophic stress levels.

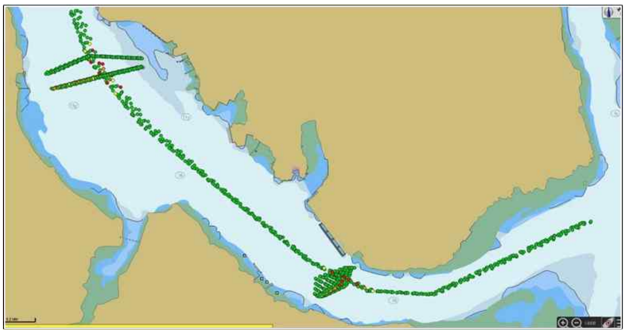

Fig. 9 Visualization of yotal ESS values in mombasa channel

The ESS values for the Likoni route, Mtongwe crossing, and main transit traffic were detailed in Table 2, with the dynamic changes in ESS values over simulation time depicted in Fig.10. Kang et al. (2022) highlighted that an ES value of 750 or more, accounting for 10% or more of the total ES value in each area, signals a significant collision risk, necessitating urgent safety measures. Interestingly, the simulation results indicated a relatively lower risk level, with only 3.2% of the total ESS values in the Mombasa Channel falling into this high-risk category.

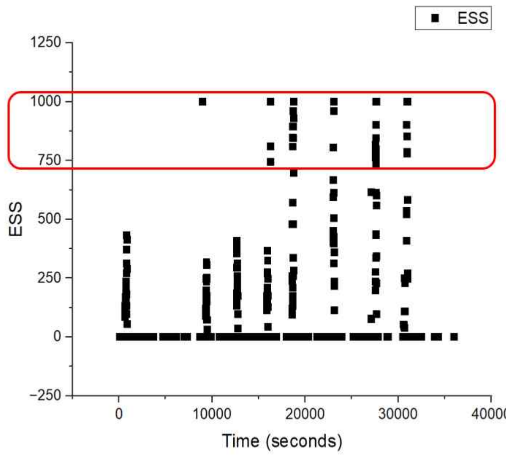

Fig. 10 ESS values changing over time (red boundary showing unacceptable ESS Values)

Table 2 ESS Values for the likoni crossing, mtongwe crossing and main transit traffic

Stress Values	Likoni Crossing		Mtongwe Crossing		Transit Traffic		Total	
	Frequency	%	Frequency	%	Frequency	%	Frequency	%
900<ESS≤1000	8	2.3	4	1.0	13	2.5	25	2.0
750<ESS≤900	3	0.9	11	2.6	2	0.4	16	1.2
500<ESS≤750	3	0.9	5	1.2	7	1.3	15	1.2
0<ESS≤500	328	95.9	400	95.2	499	95.8	1227	95.6

At the Likoni ferry route, the simulation noted that 3.2% of ESS ranged between 751 and 1000 for the Likoni ferry. At the Mtongwe ferry crossing, 3.6% of the ESS values were above 751, as recorded for the Mtongwe ferry. Additionally, the main transit traffic saw 2.9% of its ESS values fall into the critical range of 750 and above, indicating unacceptable stress levels. Overall, 3.2% of the total ships navigating through the Mombasa Channel during the simulation exhibited ESS values within the concerning range of 750 to 1000, as illustrated in Fig. 11.

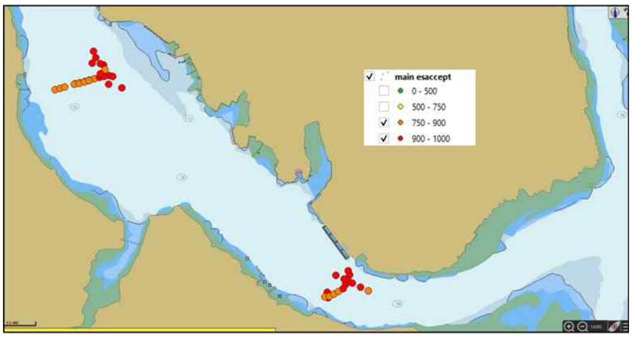

Fig. 11 ESS values above 750

The results highlight the diverse environmental stress levels imposed on navigators when traversing the Mombasa Channel's various segments. The Likoni and Mtongwe crossings, each with unique stress distribution patterns, reveal a significant number of mariners experiencing elevated stress levels. Particularly noteworthy is the main transit traffic's environmental stress on the mariner, illustrating the widespread navigational challenges faced by transit ships as they interact with crossing ferries. This situation emphasizes the critical need for specific measures aimed at improving navigational safety and efficiency within the channel.

4.1.1 Speed Scenarios

The original scenario simulated varying speeds for all transit ships to accurately reflect the real traffic conditions in Mombasa Channel. This simulation revealed that high ESS Values exceeding 750 were predominantly observed at the two ferry crossings. This suggests that the fluctuating speeds of transit ships, particularly during their interactions with ferries at these crossings, contribute to increased stress levels.

Following the analysis, the investigation focused on identifying speeds that resulted in lower ESS values to determine safe operating speeds for transit ships at the Likoni and Mtongwe ferry passages. Drawing inspiration from Wang et al. (2020), who analyzed average ship speeds in the Shanghai section of the Yangtze River to evaluate speed limits' appropriateness, this study similarly utilized AIS data to ascertain average speeds for vessels navigating the Mombasa Channel's crossings. The average speed for transit ships at the Likoni crossing was found to be 9.7 knots, while at the Mtongwe route, it was 8.3 knots. Based on these findings, two scenarios were developed to examine how ferry and transit ship interactions vary with ship speeds at these critical points:

1) 8.3 knots Scenario: The first scenario was whereby all the vessels were transiting at speed of 8.3 knots.

2.) 9.7 knots Scenario. The second scenario was set up as whereby all the transit vessels were moving at 9.7 knots.

The results of the total ESS values for both 8.3 knots and 9.7 knots scenarios were generated from the simulation and tabulated in tables 3 and 4 respectively.

Table 3 ESS values frequency distribution for 8.3 knots speed scenarios

Stress Values at 8.3 Knots	Likoni Crossing		Mtongwe Crossing		Transit Traffic		Total	
	Frequency	%	Frequency	%	Frequency	%	Frequency	%
900<ESS≤1000	8	0.3	0	0.0	5	0.8	13	1.0
750<ESS≤900	3	0.9	0	0.0	0	0.0	3	0.2
500<ESS≤750	2	0.6	0	0.0	1	0.2	3	0.2
0<ESS≤500	329	96.2	0	0.0	614	99.0	1363	98.6

Table 4 ESS values frequency distribution for 9.7 knots speed scenarios

Stress Values at 9.7 Knots	Likoni Crossing		Mtongwe Crossing		Transit Traffic		Total	
	Frequency	%	Frequency	%	Frequency	%	Frequency	%
900<ESS≤1000	4	1.2	0	0.0	2	0.4	6	0.5
750<ESS≤900	1	0.3	0	0.0	0	0.0	1	0.1
500<ESS≤750	3	0.9	0	0.0	9	1.7	12	0.9
0<ESS≤500	334	97.7	0	0.0	520	97.9	1274	98.5

In the scenario simulating a speed of 8.3 knots, only 1.2% of the total ESS values exceeded 750, while in the 9.7 knots scenario, this value was even lower, at 0.6%. This indicates that both speed scenarios led to a decrease in ESS values over 750 when compared to the baseline scenario at 3.2%, with the 9.7 knots setting showing a substantial 81% reduction in high ESS values, versus a 63% reduction observed at 8.3 knots. Notably, during these simulations, the Mtongwe crossing did not register any ESS values, suggesting that the adjusted speeds could mitigate stress significantly, as illustrated in Fig. 12 and Fig. 13 for 8.3 knots and 9.7 knots scenarios respectively.

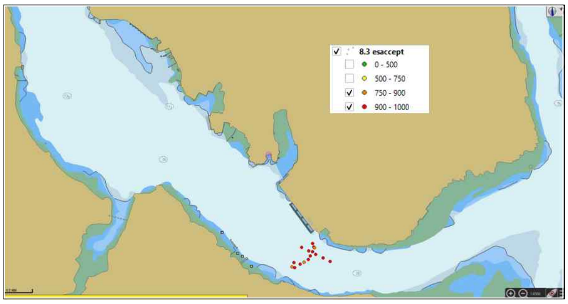

Fig. 12 ESS values above 750 at 8.3 knots

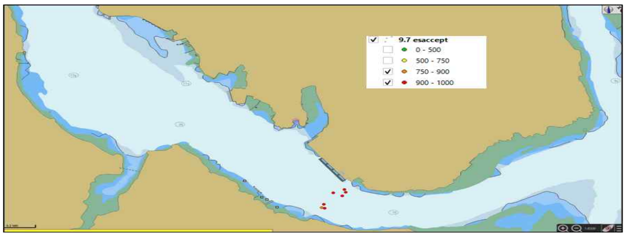

Fig. 13 ESS values above 750 at 9.7 knots

From ES model simulation, it was determined that implementing uniform speeds for transit ships, when underway in the channel and particularly at the two ferry routes, significantly reduces interaction variability, streamlining traffic and minimizing the potential for accidents from sudden maneuvers. This speed uniformity decreases the risk of collisions, particularly where ferry and transit paths intersect in the Mombasa Channel. A study by Qu et al. (2011) on the Singapore Strait, utilizing AIS data, employed a speed dispersion index to assess ship collision risks, finding increased danger in specific straits segments. Notably, 25% of cargo ships exceeded recommended speeds, heightening collision chances. The study findings emphasized that adhering to established speed guidelines could substantially improve maritime safety. Therefore, it's advised to mandate uniform speed limits for all transit vessels, especially when navigating near ferry crossings, to mitigate collision risks with ferries, thus enhancing safety in these vital areas. Furthermore, incorporating advanced navigation systems and establishing clear traffic management protocols are essential steps to complement speed regulation efforts and further improve safety outcomes. This proactive approach towards uniform speed regulation, supported by technological and procedural enhancements, is crucial for maintaining navigational safety within busy and narrow maritime channels like Mombasa Channel.

4.2 IWRAP Mk2 Model

Density plots were generated, as depicted in Fig. 14. The color coding denotes varying levels of vessel concentrations, with dark blue color indicating the highest concentration, particularly evident at Likoni crossing, and the white color representing the lowest ship density within the waterway.

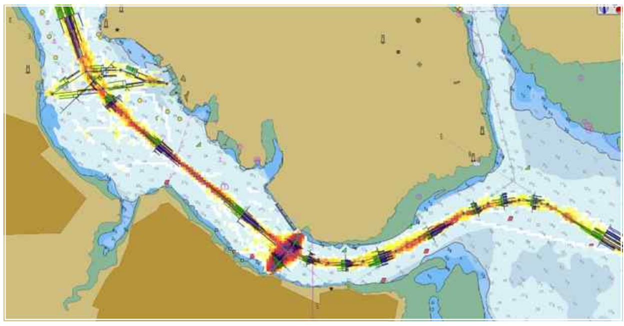

Fig. 14 Visualization of traffic density distributions in mombasa channel

In a previous study on Mombasa channel, Otoi et al. (2016) applied IWRAP Mk2 simulation at Likoni route and the findings showed that the crossing zone displayed the highest risk of collision due to crossing. Similarly in this study, the results of the IWRAP Mk2 simulation as displayed in Table 5 show that crossing collision exhibited a probability of occurring at 0.006289 incidents per year which was the highest of all collision types. This can be attributed to the high ferry traffic from the ferries crossing Likoni. Additionally, the likelihood of collisions at bends closely had a collision probability rate of 0.004366 incidents per year. This correlation can be attributed to the curvature of the bend in the channel's approach area. Other collision types including overtaking and head-on showed lower probability values, and the total predicted collision frequency in the research area amounted to 0.014702 incidents per year.

Table 5 IWRAP Mk2 collision probabilities in mombasa channel

Incident	Probability (Incidents/Year)
Overtaking	0.000354
Head-On	0.003693
Crossing	0.006289
Merging	-
Bend	0.004366
Area	-
Total Collisions	0.014702

The IWRAP Mk2 simulation results highlight the critical necessity for proactive strategies to bolster safety, especially at the densely trafficked Likoni crossing. The Kenya Ports Authority (KPA) is urged to adopt specific measures aimed at mitigating risks, including the development of effective traffic management strategies, the improvement of navigational aids, the enforcement of speed regulations, and the enhancement of port infrastructure. Such initiatives will contribute significantly to minimizing the potential for collision accidents and enhancing the overall safety of maritime operations within this waterway.

5. Conclusion

This study utilized the ES simulation model to assess the current maritime traffic conditions in the Mombasa Channel and the stress levels faced by navigators. The findings showed that stress levels, represented by ESS values exceeding 751, were notably high at the ferry crossings, affecting 3.2% of both ferry and transit navigators. This elevated stress was largely due to the varying speeds of transit ships as they navigate through the ferry crossing areas, highlighting the impact of speed fluctuations on navigational stress.

An impact assessment explored the effects of standardizing speeds for transit vessels approaching and navigating through ferry crossings on ESS values. The assessment showed a significant decrease in high ES values when transit vessels adhered to uniform speeds of either 8.3 knots or 9.7 knots. Moreover, the IWRAP Mk2 simulation identified that the total collisions were predicted to be 0.014702 incidents per year. Notably, the crossing collision probability was highest among all collision types and this can be connected to the daily heavy traffic of Likoni ferries crossing the channel.

The findings illuminate the complexities surrounding ferry crossings in the Mombasa Channel and their impact on broader maritime traffic. Understanding the challenges navigators face and the increased risk of collisions during ferry operations enables key stakeholders, including the Kenya Ports Authority (KPA), to develop specific mitigation tactics such as enforcing speed limits for transit ships when navigating at the ferry crossing sections. These strategies are essential for improving navigational safety and ensuring the efficient movement of vessels through this vital maritime passage.

The limitations of this paper included the omission of vessels transiting Mombasa Channel without installed AIS transponders such as smaller non-commericial ships. Future research should focus on integrating supplementary data sources to capture a more comprehensive view of maritime traffic in the channel. Furthermore, future studies will aim at investigating the grounding probabilities in Mombasa channel due to its narrow topographical features.

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