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SCENARIO BASED VERIFICATION AND VALIDATION OF AUTOMATED DRIVING VESSELS

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ABSTRACT

The main objective of this research is to develop a simulation-based test track for the verification and validation (V&V) of automated sailing vessels. In order to benefit from the experience of the automotive industry, traffic accident research and V&V methods in this field have been analyzed. In this paper, the effects of traffic separation in maritime traffic are analyzed on the basis of traffic separation in road traffic. Examples of the typical behavior of seagoing vessels are presented based on the analysis and evaluation of historical data collected worldwide in the context of maritime traffic separation. In order to effectively and sustainably use traffic separation systems for V&V, the open test space of the world's oceans is clustered using a methodical approach. This results in a test track for automated driving ships, which is integrated into the simulation and used for V&V through implemented scenarios.

1 INTRODUCTION

Traffic separation is a critical aspect of road safety. Intersections are complex areas of road traffic where two or more roads meet and direct vehicles in their respective directions. It is, therefore, essential that intersections are designed and maintained with safety in mind. The primary purpose of intersections is to allow vehicles to turn in different directions to reach their intended destinations. Intersections can be dangerous, because vehicles and pedestrians can occupy the same space at the same time. Drivers must make quick, informed decisions based on several factors, including their route, the geometry of the intersection, and the speed and direction of other vehicles. A small error in judgment can result in significant accidents and delays.

Drivers must, therefore, exercise caution and remain alert at all times to ensure the safety of all road users. Intersection analysis is critical to traffic management, especially in urban areas, as it has a significant impact on traffic flow and road capacity. To ensure efficient and safe traffic management, it is essential to thoroughly analyze intersections from both an accident and capacity perspective. It is important to note that the number of conflicts at an intersection can vary depending on the type of intersection. When analyzing a typical four-lane intersection, as shown in Figure 1, it is important to consider the potential conflicts that may occur. Through traffic and right-turning traffic may compete in up to eight conflicts, while through traffic alone may face up to four conflicts.

To mitigate these conflicts and provide a safer environment for all users, appropriate measures such as traffic signals and pedestrian crossings should be implemented. Similarly, left-turning traffic and turning traffic can each create up to four conflicts. These conflicts must be managed to ensure the safety and efficiency of the intersection. A typical four-lane intersection has approximately thirty or more different types of pedestrian conflicts on all four approaches.

Various types of grade separators, such as flyovers and interchanges, are used to separate traffic in the vertical plane, especially where a railroad crosses a road. In general, the road layout is divided into overpasses and underpasses. If the road with heavy traffic is elevated, an overpass is built to facilitate traffic movement. When two roads intersect, the decision to build an overpass or an underpass is based on the

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traffic volume of each road. Similarly, if the main road is lowered to a lower level, an underpass is built to allow it to cross another road via a bridge or tunnel.

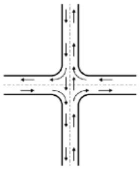

Figure 1: Typical four-lane road intersection.

Approximately 25 % of traffic accidents in Germany occur when turning or crossing a road, according to the ADAC (2022). The elimination of traffic separation may impact the classification of accident causes.

Therefore, it is crucial to thoroughly evaluate all potential consequences before implementing any changes, particularly in the field of autonomous driving. It is of paramount importance that autonomous vehicles remain within their designated lanes, observe and respond to surrounding traffic, and comply with all applicable traffic regulations. With regard to the development of automated sailing ships, it is of particular relevance for maritime research to investigate whether traffic separation within this domain poses comparable hazards to road traffic and to ascertain the reasons for this. This paper examines the challenges of traffic separation in the maritime sector for automated control of seagoing vessels, as well as the verification and validation (V&V) of such systems using simulation.

Verification is the process of evaluating the specifications and constraints imposed on an automated sailing ship. The validation process entails a comprehensive examination of these ships and its requisite systems to ascertain their suitability for automation and to determine the extent to which they align with the existing International Regulations for Preventing Collisions at Sea (COLREGs).

The research is guided by two questions:

1. What are the challenges of maritime traffic separation for automated sailing shipping? and
2. How can maritime traffic separation support V&V of these ships?

It is the authors’ understanding that there are still individuals on board automated sailing ships. In such vessels, the human operator may choose to relinquish control of a specific function, such as course control, to the automation. Such an action is not abrupt, but rather gradual in terms of information gathering and analysis (i.e., identifying an appropriate time and location to transfer course control) as well as decision making and implementation of the action (i.e., activating the course controller).

2 RELATED WORK

Maropoulos and Ceglarek (2010) provide an overview of the industry's V&V efforts, emphasizing the importance of verifying and validating complex products and processes. Bringman and Kramer (2008) provide a detailed account of the impact of model-based design on the automotive industry. The study illustrates the utilization of models in deriving test cases at various stages of the product life cycle, with a focus on model-based testing of automotive systems. Dubois et al. (2010) propose a model-based method for V&V to ensure that the final product meets the original requirements.

In the maritime domain, some on-board systems have started their evolution towards higher levels of automation. For example, the ECIDS manufacturer TOTEM has added functionality where the officer of the watch receives "decision support" according to the COLREGs based on Automatic Radar Plotting Aid (ARPA) and Automatic Identification System (AIS) data. Today's dynamic positioning systems already have the functionality to steer the ship as a traditional autopilot. Most of them also have "follow track" functionality, which is also configurable to run as part of redundant systems. Thus, a remake of a Dynamic Positioning Controller (DPC) with sense and avoidance software could be the way forward.

In light of this, a growing number of studies have been published by different institutions that cover a range of technical, operational, and legal aspects of ship autonomy (cf. Chae et al. 2020 and Hannaford et al. 2022). While several maritime stakeholders are examining the potential for increased efficiency and profitability through autonomy, these objectives remain contingent upon the assurance of safety (Chaal et al. 2022 and de Vos et al. 2021). In this regard, numerous studies have underscored the importance of research on the safety and reliability of autonomous ships in order to achieve the objective of maritime policy-makers for safer and more-efficient future shipping (Bahootoroody et al. 2022).

The objective of the International Maritime Organization (IMO) is to integrate new and developing technologies into its regulatory framework. In doing so, IMO seeks to balance the benefits derived from these technologies against concerns regarding safety and security, the impact on the environment and on international trade facilitation, the potential costs to the industry, and their impact on personnel, both on board and ashore.

The IMO aims to ensure that the regulatory framework for Maritime Autonomous Surface Ships (MASS) remains aligned with the rapid evolution of technological developments. At present, maritime research and industry are primarily engaged in the optimization of assistance systems, including those designed to prevent collisions, optimize routes in consideration of meteorological conditions, and reduce fuel consumption. The aforementioned assistance systems represent a fundamental prerequisite for the operation of autonomous ships.

A review of the literature revealed no existing research that addresses the implementation of a maritime test track in a simulation for automated sailing ships or their models and required assistance systems.

3 METHODOLOGICAL CRITICALITY ANALYSIS FOR AUTOMATED SAILING VESSELS

During the 2000s, numerous maritime projects emerged with a focus on researching and developing autonomous operations. In 2017, Rolls-Royce successfully demonstrated the world's first remotely operated tug in Copenhagen harbor. Additionally, the Advanced Autonomous Waterborne project, a joint research effort with several universities and industry representatives, has received significant attention.

The AAWA Applications Initiative conducted a study on sensor technology and the optimization of existing communication technologies for autonomous ship control. These initiatives demonstrate the commitment of the maritime industry to advancing autonomous technology while prioritizing safety and efficiency. The MUNIN project, conducted from 2012 to 2015, aimed to develop and verify the concept of autonomous ships through Maritime Unmanned Navigation through Intelligence in Networks. Other projects aim to achieve autonomous operations, demonstrating the availability of the technology. This ensures that the necessary safety and security measures are in place. With the appropriate approach, a successful and safe transition to autonomous operations can be achieved.

Although there may not be directly comparable V&V methods in the maritime literature to those used in automotive research, some of their principles can still be applied. The criticality analysis method (Neurohr et al. 2021) can lead to a more reliable and confident approach to V&V in the maritime industry. This method has been evaluated for urban intersections and analyzes the open context of urban traffic. Relevant influencing factors, known as criticality phenomena (CP), are factors that can increase the likelihood of a critical scenario. It is important to acknowledge that CPs represent hazard classes. The core steps of the criticality analysis involve a three-step process (Figure 2). First, the CPs are extracted. Second, the understanding of the CPs is enhanced by identifying underlying causal relationships. Finally, abstraction and classification of causal relationships are utilized for scenario space condensation. The objective when considering a CP is to improve the understanding of the underlying causal relations. To accomplish this, a plausible causal model is developed to explain how this phenomenon heightens criticality. An expert first proposes a hypothetical causal relationship to account for the phenomenon. Then, empirical analyses are used to collect evidence supporting the plausibility of the proposed causal relationship. The hypothesis is refined through iterative learning, which involves expanding the dataset, continuously updating the ontology, and utilizing metrics and simulation models. If the statistical evidence is sufficient to verify and validate a causal relationship, it is considered a credible explanation for the phenomenon. To analyze maritime transport segregation based on criticality, it is essential to first identify the critical points. Utilizing available knowledge or data can lead to a more confident and accurate analysis. Historical AIS data from a variety of freely available and commercial sources is utilized to identify these points at and within maritime traffic separation lines.

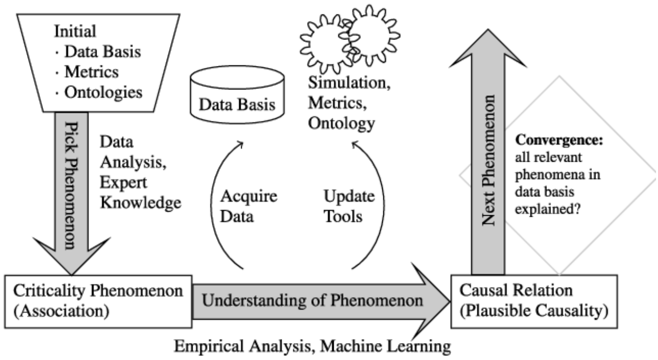

Figure 2: Basic concept of the criticality analysis (Neurohr et al. 2021).

To digitally evaluate the AIS data available worldwide, the data contained in 27 different messages must be decoded and processed using a parser. This process involves pre-processing to improve the quality of the trajectory data and generate sub-trajectories. The pre-processing includes three steps:

- *Trajectory Extraction and Separation* involves two sub-steps: extracting data from different vessels and separating data from different trajectories of the same vessel. Vessels are identified by their Maritime Mobile Service Identity (MMSI). The vessel's trajectory may be discontinuous in different time periods and different trajectories of the same vessel can be separated based on the time stamp of the AIS data.
- There is a specification for a *time interval standardization* of the AIS data transmission time interval. However, many AIS data acquisition time intervals violate the standard (Shuang et al. 2020).
- *Data cleansing* involves removing impossible positions or trajectories from longitudinal and latitudinal data of ship AIS that are derived from the Global Positioning System (GPS) (Shuang et al. 2020). GPS-relative positioning is subject to errors due to atmospheric delay, multipath, and diffraction. To ensure accuracy, specific constraints are used to discard erroneous data.

4 MARITIME CP AT TRAFFIC SEPARATION LINES

One important matter to address is the improper entry and exit of vessels from Traffic Separation Schemes (TSS) in accordance with Rule 10 of the COLREGs. Vessels must enter or exit at the end of the lane (Figure 3a). When entering or exiting from one side, it is advisable to do so at the smallest possible angle to the general direction of travel.

According to Figure 3b, the vessel exhibits a critical behavior by turning into incoming traffic after leaving the TSS. This behavior may result in close quarters situations and an increased risk of collision. Figure 3c illustrates the assessment of historical AIS data for a vessel (dotted line) that deviates from the prevailing direction of traffic within a TSS. This action contravenes Rule 10 of the COLREGs, thereby endangering other vessels within the TSS. The vessel's planned waypoint (white circle) is correctly positioned in the center of the TSS, indicating that the route was likely planned correctly but not followed.

The vessel's behavior in Figure 3d is also of significant importance, as it demonstrates a clear avoidance of entering the TSS, as evidenced by the dashed AIS data line. The vessel's planned waypoint (white circle) is situated within the TSS, suggesting that the route was correctly planned but not followed. The AIS data indicate that the TSS is being navigated in violation of the established rules. The ship's turning at the end of its intended direction and into oncoming traffic represents a critical hazard.

Similarly, ships transiting a lane must travel in the direction of that lane. However, there may be vessels navigating within the lane that are not proceeding in the appropriate direction. For instance, vessels fishing within the traffic lane may be doing so contrary to the traffic flow due to weather and tidal effects. Similarly, sailing vessels may be unable to conform to the general direction of traffic flow due to wind direction. While these vessels are directed not to impede the passage of a vessel following a traffic lane, they may not always comply with their obligations. Therefore, ship officers should approach such situations with a high degree of caution. Assuming that the fishing or sailing vessel will take appropriate action may cause a delay in acting to avoid a collision, which is a direct contravention of COLREGs Rule 8, Action to Avoid a Collision.

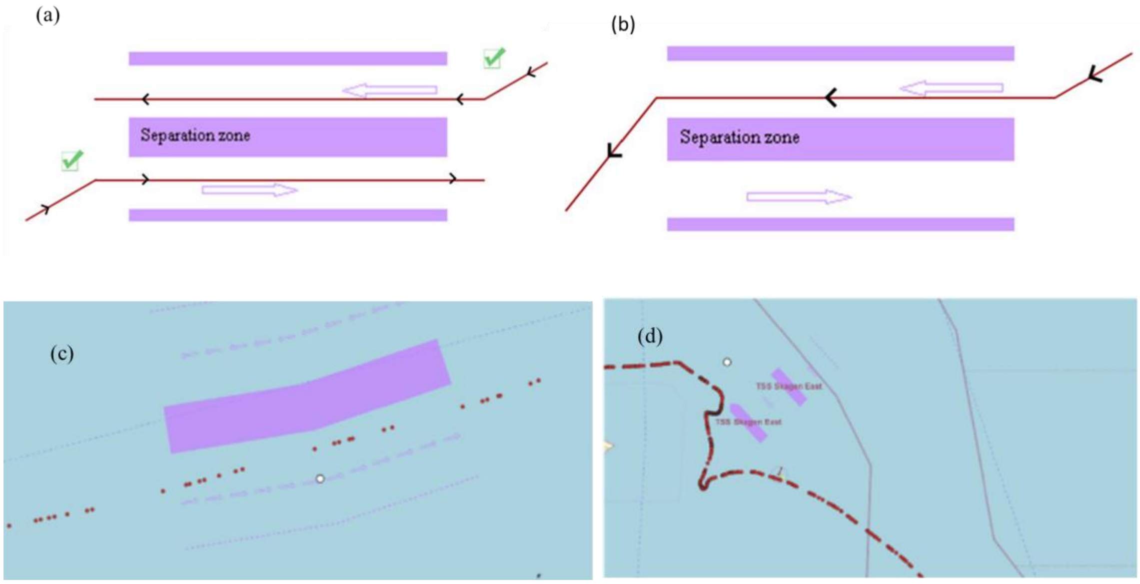

Figure 3: Criticality phenomena joining and leaving TSS: (a) proper use of a TSS; (b) exiting a TSS incorrectly; (c) non-compliance with the general direction of travel; (d) correct planning with deviating execution and causing irritation to other road users.

Figure 4a illustrates a vessel using a lane designated for reaching a port (blue arrow), but the vessel does not intend to call at this port and instead returns to the original separation line. This behavior, turning into following traffic, is already implemented in the route planning, as shown by the waypoints (white circles). Abnormal behavior related to TSS is another critical phenomenon. Figure 4b shows a vessel crossing the TSS (dashed AIS message) and then returning to the original separation line. The vessel's waypoint planning (white circles) was mostly correct, except for one waypoint which was incorrect (indicated by the red arrow).

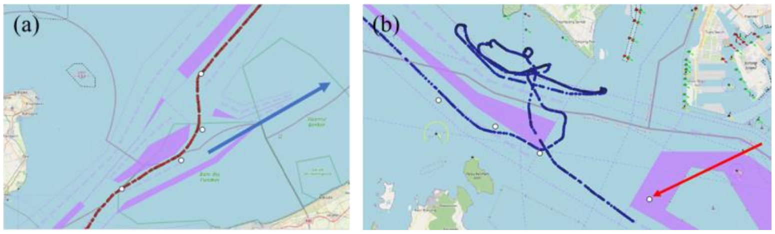

Figure 4: Behavior related to TSS: (a) improper use; (b) abnormal behavior.

Regulation 10 (c) of the COLREGs requires ships to avoid crossing traffic lanes whenever possible. If crossing is necessary, ships should do so at a right angle to the general direction of traffic. It is important to note that critical situations may arise, such as when a pilot must to be picked up and the TSS needs to be crossed. Figure 5a depicts a critical situation in which a vessel attempts to cross the TSS (black arrows) while sailing on the right (outer) side of the TSS, requiring it to cross the oncoming traffic (red arrows).

Good seamanship dictates sailing on the inside of the TSS so that the oncoming traffic is on the starboard side and does not need to be crossed (Figure 5b).

Figure 6a illustrates a vessel crossing that was planned using the white circle waypoints. However, the execution of this plan was not optimal, as evidenced by the dashed line (AIS messages).

To strengthen the causality between criticality phenomena and traffic segregation, 200 marine accident reports have been analyzed and several correlations found. For example, a collision occurred between the vessels SPRING GLORY and JOSEPHINE MÆRSK in the Eastern approaches to the Singapore Strait, approximately 7 nm NE of Horsburgh Lighthouse (Figure 6b) (DMAIB 2013). According to the COLREGs, SPRING GLORY was required to give way, and JOSEPHINE MÆRSK was required to stand on. The procedure for avoiding collisions within TSS is identical to the procedure for avoiding collisions outside of TSS. Similarly, the procedure for passing within TSS is the same as the procedure for passing outside of TSS. In critical situations, such as when a vessel enters a separation line as shown in Figure 5c, Rule 10 (b) (iii) of COLREGs applies: “A vessel using a traffic separation scheme shall: normally join or leave a traffic lane at the termination of the lane, but when joining or leaving from either side shall do so at as small an angle to the general direction of traffic flow as practicable”. The COLREGs do not specify the exact size or range of angles.

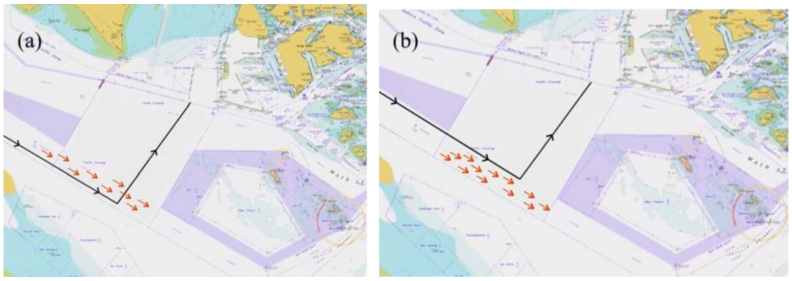

Figure 5: Crossing a TSS: (a) bad seamanship; (b) good seamanship.

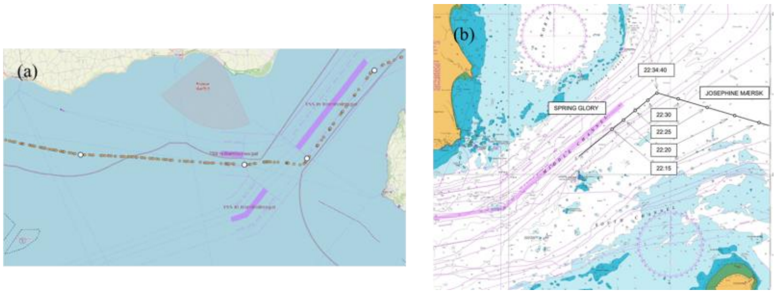

Figure 6: Behavior within a TSS: (a) Ship behavior difficult for others to assess; (b) Collision in a TSS.

5 POSE AND APPLICATION LEVEL

The objectives of a vessel traffic management system are to mitigate specific hazards. These hazards include reducing the risk of collision by separating opposing traffic flows, reducing the risk of collision between intersecting traffic and vessels in established lanes, simplifying traffic flow patterns in converging areas, and organizing safe traffic flow in areas of concentrated offshore exploration or exploitation. The aim of organizing traffic flow is to minimize the likelihood of accidents in hazardous or undesirable areas, similar to the separation of automobile traffic.

In areas where water depth is unsafe or critical, ships are specifically diverted to reduce the risk of grounding. Additionally, traffic is redirected to avoid disrupting fishing activities in fishing grounds. Traffic routing systems are composed of several elements, including TSS, lanes, separation zones or lines, traffic circles, near-shore traffic zones, recommended routes, deep water routes, caution zones, and areas to avoid. It is important to use precise terminology when referring to each of these elements to ensure clarity and avoid confusion.

Maritime traffic separations have been established at great distances worldwide. To structure this open context, a methodological criticality analysis was developed (see Figure 2). The approach maps an infinite-dimensional space onto a finite set of artifacts, which can capture and explain critical situations for automated moving vessels. This analysis uses a combination of expert-based and data-driven methods to identify relevant phenomena and explain the underlying causalities. The process is concise and leads to a manageable collection of artifacts.

Prior to designing an automated sailing vessel, a criticality analysis is performed, which is not included in the applied process model. The open context is examined independently of a specific implementation to ensure applicability to all automated vessels. The data obtained can define safety principles and risk mitigation mechanisms for automated ship operations. It can also serve as a safety argument for the most comprehensive approval process.

Similar to automotive research, an autonomous sailing vessel must be capable of navigating in separate lanes and avoiding obstacles without colliding with oncoming traffic. To achieve this, it is necessary to group the infinite test space into a manageable number of artifacts for V&V, rather than simulating driving through globally distributed maritime traffic separations. The methodical criticality analysis is used to achieve this grouping by combining different types of traffic separation. The artifact reduction of the test space for maritime traffic separation is shown in Table 1 and visualized in Figure 7.

Table 1: Artifact reduction of the test space.

Ident No.	Kind of Separation
1	Safety Fairway
2.1	Traffic Separation Scheme (TSS), traffic separated by separation zone
2.2	Traffic Separation Scheme, traffic separated by natural ~~obstractions~~obstructions
2.3	Traffic Separation Scheme, with outer separation zone separating traffic using scheme from traffic not using it
3	Traffic Separation Scheme, roundabout with separation zone
4	Traffic Separation Scheme, with “crossing gates”
5	Traffic Separation Scheme crossing, without designated precautionary area
6	Precautionary Area
7.1	Inshore Traffic Zone (ITZ), with defined end limits
7.2	Inshore Traffic Zone, without defined end limits
8.1	Recommended direction of traffic flow, between traffic separation schemes
8.2	Recommended direction of traffic flow, for ships not needing a Deep-Water (DW) route
9.1	DW, as part of one-way traffic lane
9.2	Two-way DW route, with minimum depth state
9.3	DW route, centerline as recommended one-way or two-way track
10.1	Recommended route, one-way and two-way (often marked by centerline buoys)
10.2	Two-way route, with one-way sections
11.1	Area to be Avoided (ATBA), around navigational aid
11.2	Area to be Avoided, e.g. because of danger of stranding
12	Pilot House

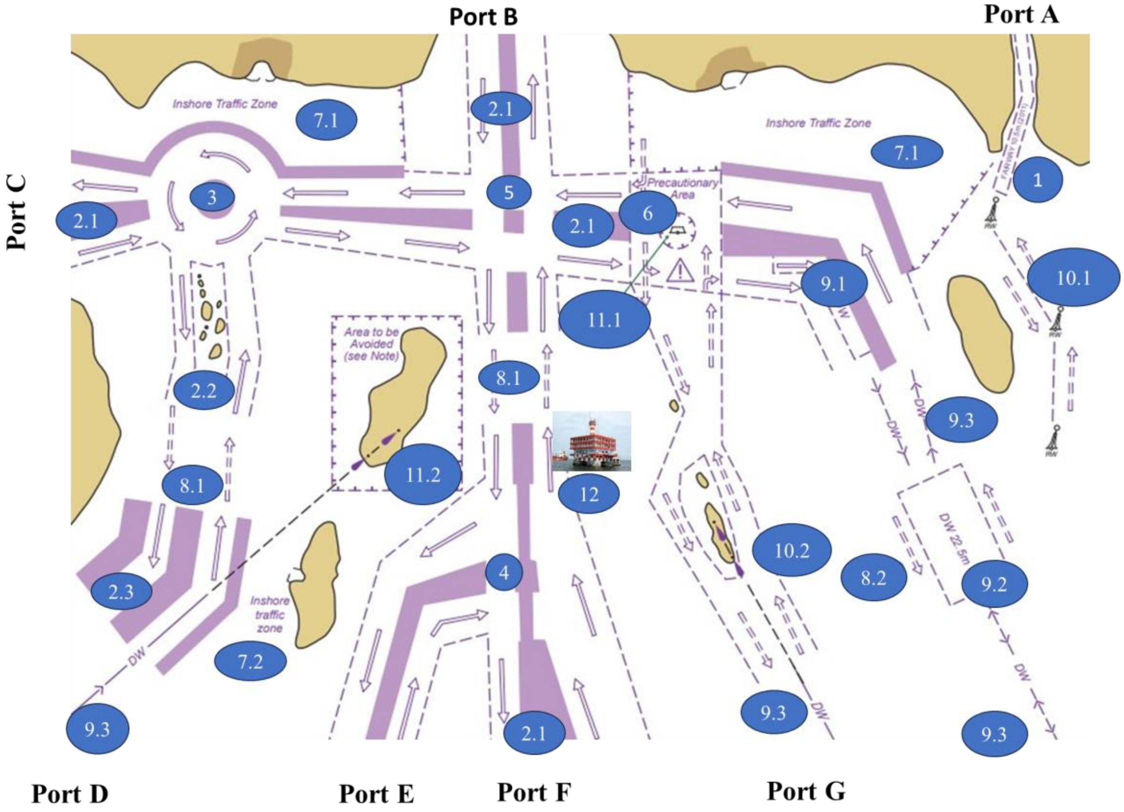

Figure 7: Reduction of the open maritime test area of traffic separation through critical analysis methodology.

The criticality analysis results in a feasible and efficient test track for automated sailing shipping, encompassing the key elements of global traffic separation in maritime transport. Unlike road traffic, maritime traffic relies less on signaling, which can be omitted from the test track. The objective of the subsequent scenarios is to ascertain whether the tested system fulfills its stipulated requirements and is fit for use (verification), whether the requirements of Roles 2, 8, 10, 14, 15, 18 and 13 of the COLREGs are met, and to identify any remaining deficiencies in order to eliminate them if necessary (validation).

The validation will also examine whether the COLREGs rules under consideration are sufficient for an automated sailing ship or whether additions or modifications to the rules under consideration should be made. Proposals will be submitted to the competent authorities. This activity is supported by carrying out the following group scenarios within the simulation:

- In *Scenario Group 1*, the automated sailing ship model and its assistance systems (hereafter referred to as the "own vessel") must navigate the test route from each port to all seven other ports without errors. The objective of this scenario group is to assess the ability of the automated sailing system to recognize the respective traffic separations and navigate safely (compliance with Rule 10 COLREGs).
- For the behavior of the own ship in *Scenario Group 2*, the scenarios utilized in Group 1 are repeated, with the exception that opposing traffic from one vessel is present on each route. The objective is

the detection of oncoming traffic by the automated sailing ship and, if necessary, change of course and speed (compliance with COLREG Rule 8).

- In *Scenario Group 3*, the own ship must take a pilot. The vessel is currently navigating from Port B in direction towards Port F, while three other vessels are sailing in the opposite direction on the same route. Furthermore, since the departure of the vessel, there has been cross-traffic on the routes from port C to port H and from port D to port H. In order to pick up a pilot at Point 12, the vessel must cross the opposite direction of the traffic separation scheme in Figure 6 at Point 12 with the objective to test the behavior of the automated sailing ship when crossing traffic separations with oncoming traffic (compliance with COLREG Rule 8 and10).
- *Scenario Group 4* focuses on the analysis of the safest angles for turning into a TSS. The vessel is situated within an Inshore Traffic Zone (Point 7.1, Figure 6) and must reach port C. To accomplish this, the vessel must turn into the TSS in the direction of Point 5 while simultaneously navigating through oncoming shipping traffic heading in the same direction from Port H. In this scenario group, the vessel performs different turning angles towards the general direction of travel within the TSS, ranging from 5 to 80 degrees, while encountering oncoming traffic. The objective of this scenario group is to ascertain the turning angle into a traffic separation scheme that presents the least risk to following traffic and the vessel itself. The COLREGs do not specify a specific angle, but it should be a shallow one (compliance with COLREG Rule 8 and10).
- *In Scenario Group 5*, the own vessel is overtaken by another ship at Point 2.2 (Figure 6) on the route from port D to port C. After this scenario the same overtaking procedure occurs for the own vessel on the route from Port C to Port G at Point 10.2. In both instances, the vessel undertaking the overtaking maneuver has a speed that is five knots higher than that of the vessel being overtaken. In a different scenario, the own ship overtakes another vessel (the target vessel) on the route from Port H to Port A at Point 10.1. The ship's speed is five knots faster than the speed of the target vessel. However, there is oncoming traffic in the opposite direction during the overtaking maneuver. At Point 8.1 on the route from Port E to Port G, the own vessel performs another overtaking maneuver. Traffic is present when the own vessel enters the route from Port F, and there is oncoming traffic at Point 8.1. The vessels are employed to execute the scenarios with varying overtaking angles and distances. During overtaking maneuvers, there may be instances where the two ships come into close proximity with one another for extended periods of time. In other scenarios, one ship is significantly larger than the other one during the overtaking maneuver. In such a scenario, the larger ship may experience inconvenience due to the smaller, better maneuverable ship. In these situations, the vessels involved are bound by COLREGs Rule 13, Overtaking. Rule 13(a) requires vessels to keep out of the way of vessels being overtaken, regardless of the type of vessel or the location of the overtaking maneuver. This rule takes precedence over Rule 18, Responsibilities between Vessels, and Rule 10. Objective: Test for compliance with COLREG Rule 10 and 13.
- In *Scenario Group 6*, on the route from Port F to Port B, the own vessel encounters crossing traffic from and in the direction of Port C at Point 5. Additional crossing scenarios for the own ship occur on the route from Port D to Port C at Point 5 due to traffic entering and exiting Port C. Crossing vessels can create issues if they decide to cross TSS at an unsuitable time. While the rules do not mandate when or where a vessel can cross a TSS, it is the responsibility of the crossing vessel, whenever feasible and in the interest of good seamanship, to select a crossing point that will cause the least inconvenience to through traffic. The objective is to test for compliance with COLREG Rules 8, 15, 18 and 2.
- Within *Scenario Group 7*, various head-on situations between the own ship and a target ship are depicted. The objective is to test for compliance with COLREG Rule 14.
- *Scenario Group 8* comprises comparison scenarios between the model of the automated sailing ship and a ship of the same class and size without automation. The objective is the validation of the

automated system by determining whether it represents real added value and specifics of motion separation control of conventional and automated sailing vessels.

If assistance systems are to be tested, they will be directly integrated into the simulation or simulated for different ship classes. During each scenario execution, the behavior of the own ship and its effect on the surrounding traffic is observed, recorded and evaluated. Additionally, the behavior of the ship will be analyzed under the influence of human factors, such as fatigue and stress.

6 HAGGIS VIRTUAL MARITIME CO-SIMULATION INFRASTRUCTURE

The DLR Simulation HAGGIS virtual co-simulation infrastructure (Figure 8) includes AI-based simulators for environmental conditions, traffic, and ships. This infrastructure enables the evaluation of risks and efficiency of innovative maritime systems during product development. For instance, collision avoidance systems can be safely tested in this simulation environment without endangering people or goods.

The cognitive simulation component, CASCAS, makes HAGGIS suitable for driving on the grouping elements of traffic segregation. CASCAS emulates real human behavior by performing specific tasks (Lenk et al. 2012). The current implementation uses the High-Level Architecture (HLA) as a co-simulation architecture. The data specification of the world data model is defined in HLA-specific object model template (OMT) files, as per IEEE standard 1516. Standardized wrappers are utilized to facilitate the integration of the simulators. A semantic world data model is employed to define the data exchanged by the simulators. A tool is used to automatically control the simulation and detect rare events, along with observer components that monitor the simulation. The observer components are generated automatically using the models defined with MOPhisTo.

The Maritime Traffic Simulator (MTS) is a versatile simulator for maritime traffic that can be used to implement, execute, and observe the behavior of multiple ships in a realistic context. The simulation comprises a dynamic model for each ship, describing its response to environmental factors such as waves, currents, and wind. Additionally, an intelligent agent controls each ship to follow a predetermined course or to find its own course in accordance with maritime regulations. The physical interactions of rigid bodies within the environment can be simulated by the N-Body simulator (Schweigert et al. 2012).

To simulate simplified agent models using MOPhistTO, the authors have implemented the MASCaS model interpreter. The Sensor Simulator generates realistic sensor measurements from a simulated context, such as the context of the maritime traffic simulation. When combined with a traffic simulation, it can generate AIS or radar data. The Distributed Controlling Toolkit (DistriCT) is utilized to configure and manage simulation components on various distributed systems, including the initiation and termination of simulation components.

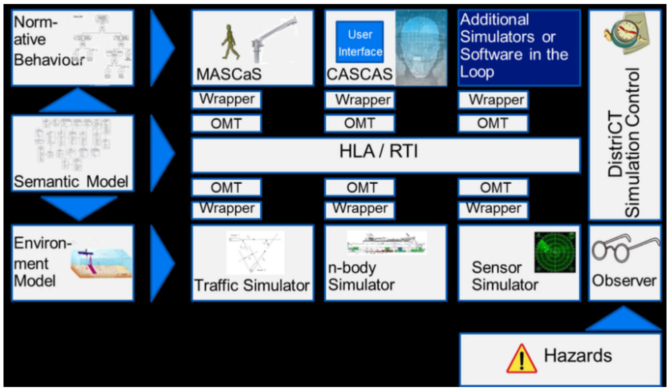

Figure 8: Screenshot of the HAGGIS co-simulation environment.

7 IMPLEMENTATION OF THE TEST TRACK

The test track that was derived is currently being implemented in the DLR maritime co-simulation. The eMIR data model utilized in HAGGIS stores Electronic Navigational Charts (ENCs) in an object-oriented structure. This structure is modeled after the International Hydrographic Organization's S-57 standard, which guarantees that all features present in ENCs displayed by Electronic Chart Display and Information Systems (ECDIS) can be handled in the HAGGIS simulation. By using a geometric representation based on the S-100 standard, with the possibility for extensions, and by covering all S-57 features, it is possible to adapt the eMIR data model to the new S-101 standard with relatively low effort.

To exchange chart data, eMIR implements import and export functions for the GeoJSON and ESRI Shapefile formats. The test track's required elements were built using QGIS and then imported into the HAGGIS scenario. These elements consist mainly of TrafficSeparationSchemeLanePart, TrafficSeparationZone, InshoreTrafficZone, DeepWaterRoutePart, RecommendedTrack, CoastLineFeatures, and LandAreaFeatures, etc., which define the environment. Example: The TrafficSeparationScheme feature type is linked to the TrafficSeparationSchemeLanePart feature through the TrafficSeparationSchemeAggregation.

The implementation of the test track in the simulation was found to be extensive and detailed to an extent that could not yet be completed. Consequently, the anticipated outcomes of the planned scenarios cannot yet be presented.

8 DISCUSSION AND FUTURE WORK

A validation experiment aims to represent the response of a component or system under the conditions it will experience during system-level operation. However, it is important to note that experiments cannot accurately reproduce all variables of the intended environment. The test device can only simulate certain aspects, and the System under Test (SuT) is often a scale-down or prototype version of the final article. It is important to consider that the sensors installed on the SuT can influence its response. The described experiment is a physical simulation of the item, component, subsystem, or system to be used in the field and its environment. The test track is unique and provides essential insights into the behavior of automated sailing vessels and their assistance systems.

In order to guarantee the safety of these vessels, it is of the utmost importance to adhere to Perera's classification (Perera 2020). He proposes a 3-step approach to validate the behavior of autonomous vessels and avoid hazards caused by software errors. At Level 1, a software simulation is used to test the movement of all vessels. Level 2 requires the vessel to be a full-size or model vessel navigating in confined waters while the other vessels are simulated. In contrast, a Level 3 system requires that all ships involved navigate in open waters. It is assumed that both the implemented test track and the simulator are suitable for conducting Level 1 assessments.

Automated sailing ship models and their assistance systems have not yet been evaluated, due to the complex and time-consuming analysis of historical AIS data in the context of global maritime traffic separation and the implementation of the test track in the HAGGIS simulation. The next priority is to focus on this task. However, the core of the two research requests can already be addressed. Automated shipping faces similar challenges to road traffic separation in achieving passive safety. Although efforts have been made to segregate maritime traffic, collisions and dangerous situations still occur due to the behavior of ships in general.

The determination of the situation depends on human perception, comprehensive situation analysis, and regulatory knowledge. Therefore, the question arises as to how safety measures can be improved. Due to the complexity of the test track in a confined space, a high level of attention, in-depth knowledge of the regulations, and extensive automation technology are required. The test track is expected to provide essential insights for automation and its optimization.

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