

Review

Towards Human Factors Evaluation of Interactions with Maritime Autonomous Surface Ships Using Full Mission Bridge Simulators: The Conventional Officer's Perspective

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Abstract

Research and development of Maritime Autonomous Surface Ships (MASS) has surged in recent years. However, questions remain regarding the safety of interactions between MASS and conventionally crewed ships in mixed-traffic environments, particularly during collision avoidance. Although the critical role of MASS technology is widely recognised, few studies have explored how these interactions may affect the behaviour of the conventional ship's Officer of the Watch (OOW). The primary aim of this paper is to explore the challenges and complexities of mixed-traffic interaction from the perspective of the conventional OOW as an active participant in collision avoidance. A collision-avoidance framework is presented as an analytical lens linking situational awareness, motion prediction, mental models, conflict detection, conflict resolution, and manoeuvre execution. This framework is used to examine challenges related to communication, COLREG interpretation, uncertainty surrounding MASS capabilities and operations, knowledge and training, and trust. We argue that these factors may influence how OOWs interpret MASS behaviour and determine whether, when, and how to intervene. To address this research gap, key research questions are formulated, and a scenario-driven methodological approach using Full Mission Bridge Simulators (FMBS) is proposed to investigate changes in OOW behaviour and decision-making during mixed-traffic encounters.

Keywords: Maritime Autonomous Surface Ships (MASS); mixed-traffic navigation; Officer of the Watch (OOW); human factors; collision avoidance; Full Mission Bridge Simulators (FMBS); situational awareness; mental models; trust; COLREGs



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1. Introduction

In recent years, researchers and industry have shown an increased interest in applying new insights and technological advancements from other domains in order to reconsider maritime operations and the role of the human within these operations [1,2]. This process is largely driven by the aspiration to make shipping more economical, ecological, and safe [1,3]. As a result, numerous projects investigate the development and implementation of Maritime Autonomous Surface Ships (MASS) in relation to productivity and navigational

safety. However, there is conflicting evidence on the relationship between MASS and safety. Recent studies suggest that navigational safety is likely to increase when autonomy is introduced in the operation of surface ships [4,5]. According to the European Maritime Safety Agency (EMSA), from 2014 to 2022, 59.1% of accident events involved human action and, when human-action events and human-behaviour contributing factors were considered jointly, the human element was related to 80.7% of the investigated marine casualties and incidents [6]. This data suggests that by removing humans from ships, there is a potential to reduce the risk of maritime casualties. In addition, MASS technology creates the opportunity to further reduce the size of ships' crew, which could ultimately lead to unmanned ships [7]. de Vos et al. [8] argue that reducing the number of people at sea may improve safety by reducing human exposure to maritime accidents, even if autonomous navigation does not reduce the number of accidents. This potential safety benefit should therefore be distinguished from the separate question of whether increased automation results in more reliable navigational performance.

However, increasing automation does not necessarily produce a proportional reduction in human-factor risk. Previous studies have identified new pathways for human error as maritime operations become increasingly automated [9,10]. A recent systematic review focusing on supervised MASS operations similarly concludes that increasing automation does not linearly reduce human-factor risk and identifies a shift from direct operational errors towards risks associated with supervisory cognition, trust in automation, mode switching and takeover, and human-machine-shore collaboration [11]. Human involvement is therefore redistributed rather than eliminated, since humans remain involved in MASS operations either on board, in Shore Control Centers (SCCs), or in shoreside roles during development, operation and maintenance [12–14]. Previous research in flight deck automation already suggested that the use of automation can also contribute to accidents and has limits [15]. For example, Onnasch et al. [16] stated that automation can outperform humans in carrying out routine tasks, but human performance is catastrophically influenced when these systems fail. Overall, improving navigational reliability remains an important objective of MASS development and a subject of ongoing academic discussion; however, improved reliability cannot yet be assumed to follow directly from reducing onboard human involvement. Although research in MASS is gaining momentum, the adoption of this technology will not occur overnight [17,18]. For example, Fonseca et al. [19] noted that MASS development is still in its infancy and that vendors' enthusiasm for this new technology is not necessarily shared by the majority of shipowners. Recent readiness assessments further show that the transition towards MASS remains constrained by unresolved technological, regulatory, infrastructural and workforce requirements [20]. Moreover, MASS should not be regarded as a homogeneous vessel category, as its operational capabilities, mode of operation, and allocation of navigational functions may differ between vessels and between phases of a voyage [21,22]. Together, these considerations create considerable uncertainty regarding how MASS technology will evolve and be introduced into maritime operations. It is, however, certain that MASS will interact with conventional human-controlled ships when they are deployed at sea and that the coexistence of MASS and conventionally crewed vessels should therefore be regarded as a prolonged operational condition rather than a brief transitional phase. Mixed-traffic navigation has therefore become a distinct safety concern, particularly when conventional vessels and MASS encounter one another during collision avoidance [23]. Navigational safety in such environments must therefore be considered not only in terms of the performance of individual vessels, but also in terms of their safe coexistence within a shared traffic environment. This concern is also reflected in the recently adopted IMO MASS Code, which explicitly aims to enable MASS and conventional ships to coexist safely without impeding or negatively affecting one another. The Code

establishes functional requirements for safe MASS operation and human oversight, but does not address in detail how conventional OOWs will interpret and respond to MASS behaviour during mixed-traffic encounters [21].

Current research recognises the critical role played by MASS technology in the dynamics of interaction within a mixed environment [24–27]. For instance, Jugović et al. [28] synthesise 307 studies into a hierarchical task analysis of MASS collision avoidance across different encounter configurations. Their review demonstrates the increasing detail with which collision-avoidance tasks are structured, while also showing that mixed-traffic encounters continue to be approached primarily through the tasks and decision processes of the autonomous vessel. This MASS-centred orientation is also evident in studies addressing the importance of transparency in Artificial Intelligence (AI) controlled MASS collision avoidance manoeuvres [29,30]. In addition, Alsos et al. [31] suggest different solutions in MASS communication infrastructure, such as Automatic Identification System (AIS) messages, navigation light sequences, and route exchange practices to be established. Nevertheless, more recent research has begun to frame human–MASS interaction as an integrated safety problem rather than as a purely technical challenge [32]. Similarly, studies of human–machine cooperation increasingly emphasise human-centred approaches, but mainly consider humans operating, supervising or working aboard autonomous vessels [14]. Although these studies acknowledge that MASS will interact with conventionally crewed vessels and increasingly frame such encounters as human-centred safety problems, research has focused primarily on the design, operation and supervision of the autonomous vessel. Consequently, the conventional OOW remains underexamined as an active interaction partner in mixed-traffic encounters.

The aim of this paper is to explore the challenges and complexities of interactions between MASS and conventionally crewed ships from the perspective of the conventional OOW as an active participant in collision avoidance. To this end, the paper first presents a collision-avoidance framework as an analytical lens for examining how the OOW observes, interprets and responds to MASS behaviour in mixed-traffic situations, with particular attention to situational awareness, motion prediction, mental models, conflict detection and conflict resolution. This framework is then used to structure an analysis of the challenges that may arise during mixed-traffic operations, including communication, COLREG interpretation, uncertainty surrounding MASS capabilities and operations, and trust, and to consider their potential influence on conventional ship behaviour. Finally, the paper formulates key research questions and proposes a scenario-driven methodological approach using Full Mission Bridge Simulators (FMBS) to investigate these interactions empirically. In doing so, the paper shifts the focus from the collision-avoidance performance of MASS in isolation to the reciprocal interaction between autonomous vessel behaviour and the conventional OOW's interpretation and response.

2. An Analytical Framework for Collision Avoidance in Mixed Traffic

2.1. MASS Operational Configurations and Scope of the Framework

Maritime Autonomous Surface Ships should not be considered a homogeneous category of vessels operating at a single and fixed level of autonomy. Current operational examples already demonstrate that different configurations are possible. The Belgian short-sea cargo vessel *Fast Sim*, for example, has been equipped to test remote navigation between pilot stations, with control provided from SEAFAR's Remote Operations Centre and particular attention given to communication reliability and position estimation [33]. In contrast, *Yara Birkeland* operates commercially on a restricted 11-nautical-mile route, where autonomous crossing and docking functions are used under onboard human supervision, while mooring is still performed manually [34]. These examples illustrate that

vessels commonly described as MASS may operate under different geographical and operational restrictions and with different arrangements for onboard control, remote operation, autonomous functionality, and human supervision.

The operational behaviour and capabilities of a MASS therefore depend on its Concept of Operations, Operational Envelope, modes of operation, and the allocation of functions between human and software agents. The MASS Code moves beyond a single vessel-level autonomy classification and recognises that modes of operation may change between voyage phases [21]. Rødseth et al. [22] similarly include operating conditions, ship-control functions, and the distribution of responsibilities between humans and automation within the Operational Envelope. Li et al. [35] distinguish manual, autonomous, and remote navigation modes and show that their control processes and risk characteristics differ, while Yang et al. [36] identify transitions between modes as safety-relevant because they alter the interactions between onboard, remote, and autonomous actors. These operational differences may not be directly apparent to the conventional OOW and may therefore create uncertainty during mixed-traffic interaction.

The Operational Envelope defines the conditions within which a particular MASS configuration is intended to operate. However, whether a mixed-traffic encounter remains within normal operation also depends on the condition of the conventional vessel, the availability of communication and traffic-management support, and the surrounding traffic and environmental circumstances. For the purpose of this paper, normal mixed-traffic operations therefore refer to encounters in which both vessels and the supporting arrangements operate as intended, while the relevant traffic and environmental conditions remain within their applicable operational limits. Normal operation does not imply that an encounter is simple or free from collision risk. Uncertain intentions, communication needs, close-quarters situations, and collision-avoidance manoeuvres may all occur while the vessels and supporting systems continue to function normally.

A degraded condition arises when the performance or availability of one or more relevant elements is reduced. This may concern the MASS, the conventional vessel, communication or shore-based support, or traffic and environmental conditions that approach or exceed the applicable operating limits. A fallback state refers to a predefined alternative arrangement used to maintain or restore safe operation, such as transferring control between an autonomous system, a remote operator, or onboard personnel. An emergency situation arises when the available information, system capabilities, time, or manoeuvring options are insufficient to manage the encounter through normal or fallback procedures and immediate action is required.

The analysis primarily concerns normal mixed-traffic operations, since uncertainty and differences in collision-avoidance behaviour may arise without a technical failure or emergency. Degraded, fallback, and emergency conditions are included where they materially change the interaction between the vessels or the information and control available to those involved. They are therefore treated as different operational conditions rather than as separate forms of interaction. With this scope established, the following section introduces reactive collision avoidance as the common process through which these mixed-traffic encounters are examined.

2.2. Reactive Collision Avoidance

Previous research into autonomous navigation systems has predominantly focused on collision prevention tasks in ship navigation since collision prevention is critical for navigational safety [37–41]. Different categorisations of collision prevention techniques, i.e., route planning, path planning and reactive collision avoidance, have been suggested [42–44]. The category considering the collision between two navigating vessels is reactive collision

avoidance. These perspectives are essential for the development of Maritime Autonomous Surface Ships (MASS), but they do not fully capture the interactional nature of collision avoidance in mixed-traffic environments. Kim et al. [23] identify the interaction between autonomous and conventionally operated ships as a central safety concern in mixed navigational environments and emphasise the need for compatibility between these actors. This highlights that reactive collision avoidance in mixed traffic cannot be examined solely as an isolated function of the MASS.

When analysing interactions between conventional ships and MASS, reactive collision avoidance is particularly relevant, as it addresses scenarios in which vessels are already operating in close proximity and must assess whether an evolving traffic situation requires intervention. Huang et al. [44] illustrate that the general framework of reactive collision avoidance is similar for both conventionally crewed ships and MASS. The processes which are part of this framework can be either performed by a human operator, a designated machine/computer, or every possible combination of both. This paper presents an adjusted framework represented by Figure 1, which is based on the work of [44–46].

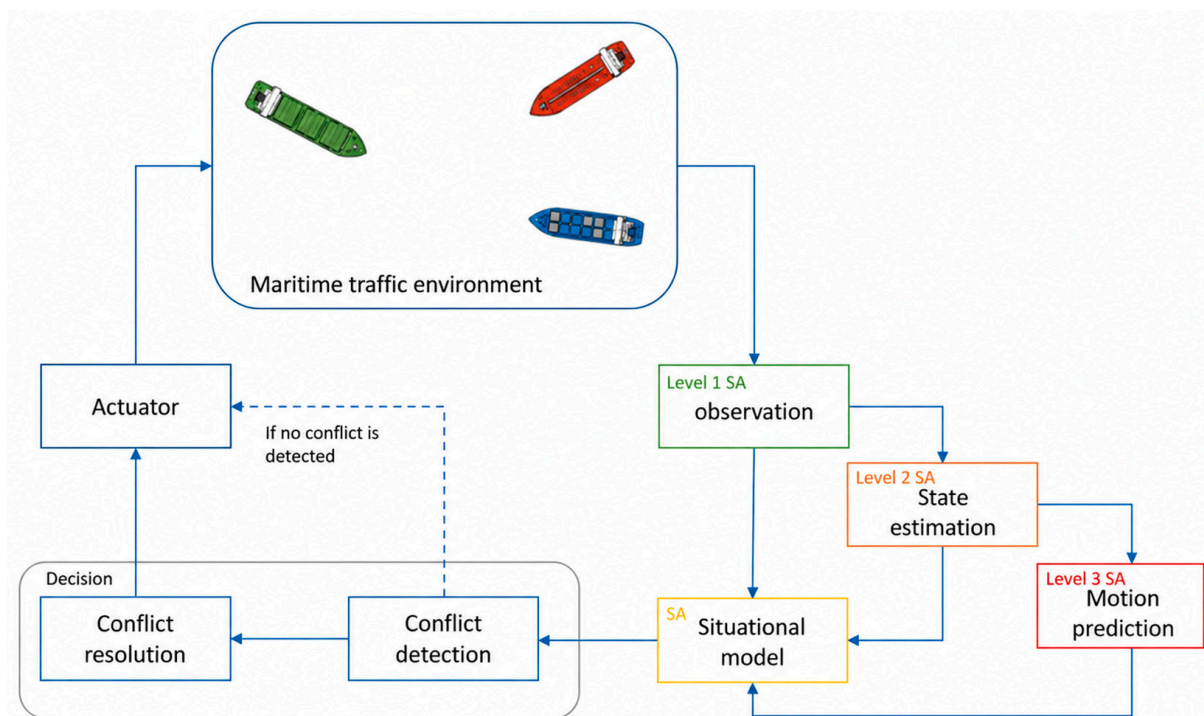


Figure 1. A collision-avoidance framework showing the interplay between factors in situational awareness and expected outcome (actuator) to control maritime traffic.

This framework is derived from the definition of collision avoidance and consists of two main processes: conflict detection, to establish whether the ship is in danger and when to take action, and conflict resolution, to determine how to avoid the collision [45]. The selected action is then executed through the vessel’s control system, whether this is a conventional bridge team, an automation-supported bridge system, a remote operator, an autonomous control system, or a combination of these. In addition, recent work on the integration of MASS similarly emphasises the interdependence among sensing, navigational assessment, decision-making, and manoeuvre execution, as well as the human and technical factors influencing these functions [28]. This supports the process-based representation of reactive collision avoidance adopted in the present framework.

2.3. Situational Awareness and Motion Prediction

Situational awareness is the cognitive basis of the shared reactive collision avoidance framework. The conflict detection process and the conflict resolution process combined are the decision block from the model presented by Endsley [46]. Endsley's model further comprises three hierarchical levels. The first level (L1) of the situational awareness model contains basic observations and perceptions of the maritime traffic environment through various machines and/or human sensory data. Once all information is collected, the Officer of the Watch (OOW) and/or system analyses this data to comprehend the current marine traffic situation and its current state. This is defined by Endsley as the second level (L2) of SA. Another important aspect of effective collision avoidance is the ability to estimate the trajectories of the obstacles and the own ship. This projection of the future status is the third level (L3) of SA. It is difficult both for human operators and machine entities to effectively reach this third level of SA as it requires accurate and robust data to construct these estimations. This third level is particularly important in collision avoidance because the OOW must anticipate whether the target vessel will maintain course and speed, alter course, communicate its intentions, comply with the COLREGs, or behave in a way that requires precautionary action. Depending on the timing of the observation, it is possible to start conflict detection and resolution processes directly from level 1 or level 2 SA. However, this has a negative impact on the accuracy and thus on the navigational safety.

Motion prediction is therefore a key link between situational awareness and collision avoidance. A vessel can only determine whether a collision risk exists if it can estimate the likely future trajectories of its own ship and target vessels. In other words, the quality of prediction is essential for collision prevention [44]. However, it remains difficult to guarantee a high-quality prediction of the target ship's motion due to insufficient information about the target ship's system inputs and navigational intentions. For MASS, uncertainty may already arise during perception and situation assessment. Sensor systems may differ in range, accuracy and integrity, while object detection and classification can be affected by sensor-specific limitations and geometric effects such as radar shadowing. Even when the same target is detected, differences in motion-prediction methods and model simplifications may result in different estimates of its position, direction or speed [47]. These differences in the constructed situation picture may subsequently propagate into motion prediction and collision-risk assessment [44,47]. As a result, a manoeuvre that is consistent with the MASS's internal assessment may nevertheless appear late, atypical, or insufficiently transparent to the conventional OOW.

A way to address this challenge of predicting the future state of a target ship is to assume that it will maintain its course and speed regardless of its route planning or environmental disturbances. However, this oversimplified assumption is not suitable for accurate collision avoidance. Huang et al. [44] distinguish three broader approaches: physics-based methods, which model vessel dynamics and environmental effects but largely neglect navigational intent; manoeuvre-based methods, which infer likely behaviour from historical traffic data using statistical or machine-learning techniques; and interaction-aware methods, which incorporate exchanged information or negotiated manoeuvring intentions. Machine-learning methods still require further evaluation for real-time risk modelling [48], and none of these approaches eliminates uncertainty about the target vessel's future actions.

Despite these recent efforts to answer the uncertainties of target ship motion prediction, most modern systems still use an oversimplified version (e.g., the first method described) of the target ship's motion model. On the other hand, systems that allow the target ship to deliberately change course and speed assume that the navigational intentions are known to the own ship or strictly bound by, for example, a strict and quantitative

approach to the Collision Avoidance Regulations (COLREGs), or “rules of the road”. Modern collision avoidance technologies need improvement in the motion prediction processes to be able to safely interact with complex maritime operational environments [44]. In mixed autonomous and human-operated traffic, trajectory prediction and adaptation take place in an inherently decentralised environment, in which human-controlled ships may make unanticipated decisions and communication channels differ in availability and performance [49]. Consequently, motion prediction should be treated as a continuously updated interaction problem rather than as a one-off estimate of a target vessel’s future path. Furthermore, Song et al. [32] demonstrate that collision avoidance in mixed traffic is iterative and interaction-dependent, and that trajectory prediction can be improved by incorporating navigational preferences derived from human-controlled vessels. Their findings reinforce that motion prediction should account not only for kinematic movement, but also for recurring navigational preferences and interaction patterns reflected in observed vessel trajectories.

For the human OOW, motion prediction is not derived from kinematic data alone. Radar, AIS and visual observations are interpreted in relation to vessel type, relative movement, navigational context and communication behaviour, while professional experience informs expectations about how other vessels are likely to behave. Prediction therefore remains provisional and must be continuously revised as the encounter develops. These expectations are structured through mental models, whose role in situation comprehension and projection is examined in the following section.

2.4. Mental Models and Preconceptions

To anticipate the future states of target vessels, OOWs necessarily rely on simplified representations of the traffic situation. One recognised failure in Level 3 situation awareness occurs when current trends are projected too far into the future without sufficiently accounting for possible changes in vessel behaviour [50]. At the same time, OOWs also use mental models to direct their model prediction process and help with the comprehension of the maritime environment. Mental models are defined by Rouse and Morris [51] as “mechanisms whereby humans are able to generate descriptions of system purpose and form explanations of system functioning and observed systems states and predictions of future states”. Endsley and Jones [50] stated that without a mental model, a person would be very poor at understanding what is happening or what is likely to happen in the future; e.g., mental models are the key enablers of level 2 (L2) and level 3 (L3) SA. Within the present framework, mental models therefore connect perceived information and current-state assessment with expectations about how an encounter is likely to develop.

In this paper, preconceptions refer to prior assumptions and expectations that direct attention and influence which mental model is applied to an encounter. While mental models enable comprehension and projection, preconceptions may therefore affect the selection and use of those models before the behaviour of the target vessel has been fully established. Figure 2 is based on the work presented in Endsley and Jones [50] and expands the situation-awareness component of Figure 1 by illustrating how goals, preconceptions and mental models influence observation, comprehension and projection.

The role of mental models in shaping situational awareness during conflict detection and resolution is particularly relevant when examining collision avoidance in mixed-traffic environments. These mental models help the OOW interpret available information and anticipate how an encounter is likely to develop. However, the uncertainty associated with these models becomes more pronounced when interacting with MASS. In conventional encounters, the OOW can generally rely on familiar assumptions about human watchkeeping, bridge-to-bridge communication, seamanship and informal patterns of

navigational behaviour. When interacting with a MASS, these assumptions may no longer hold. As a result, mixed-traffic collision avoidance is not only a matter of autonomous system performance, but also of human interpretation on the conventional ship's bridge.

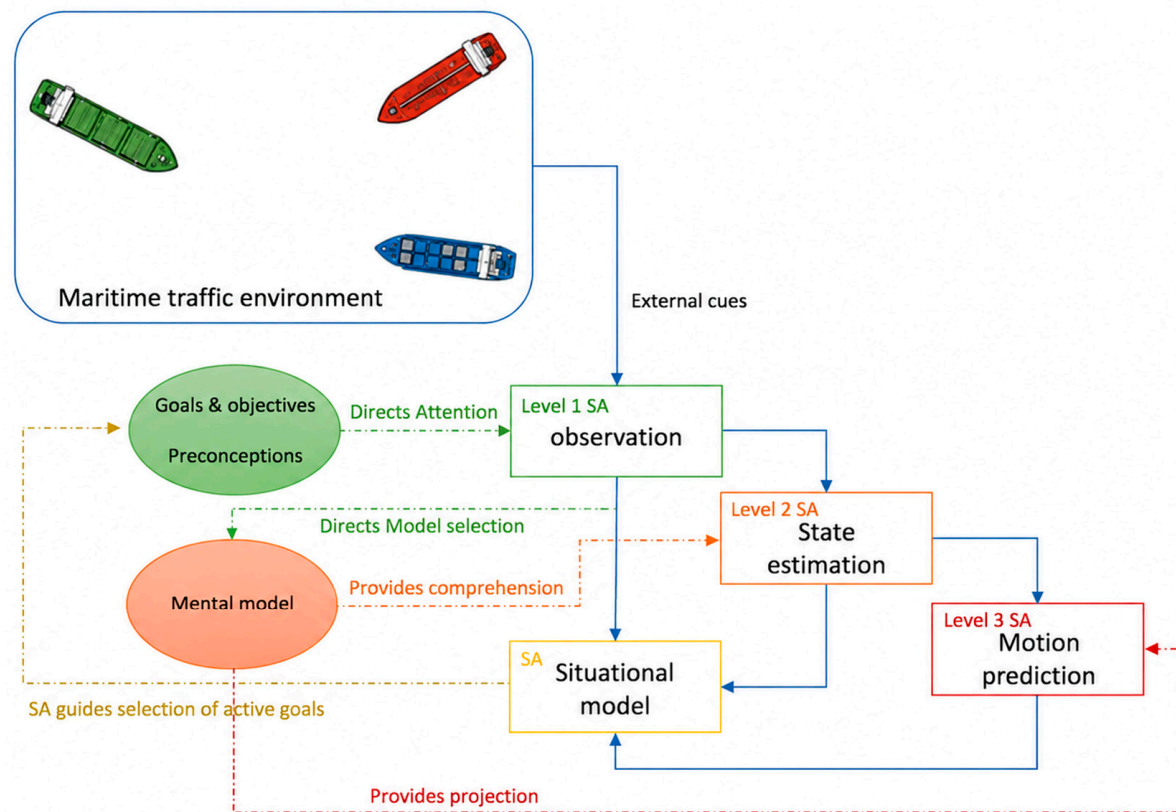


Figure 2. Influence of goals, preconceptions and mental models on the situation-awareness component of the analytical collision-avoidance framework.

2.5. Applying the Analytical Framework to Mixed-Traffic Interaction

The collision-prevention framework presented in this section provides an analytical lens for examining interactions between conventional ships and MASS. Reactive collision avoidance is particularly relevant because it concerns close-proximity encounters in which vessels must determine whether, when and how to intervene. The framework structures this process into perception and interpretation, motion prediction, conflict detection, conflict resolution and manoeuvre execution.

Situational awareness and mental models influence how the conventional OOW moves through these stages. When interacting with MASS, uncertainty may increase because familiar assumptions about watchkeeping, communication, seamanship and navigational behaviour may no longer apply. Mixed-traffic collision avoidance can therefore be understood as a reciprocal interaction between the behaviour of the MASS and its interpretation on the conventional ship's bridge. The MASS must detect risks, select a manoeuvre and execute the resulting action, while the conventional OOW must interpret that behaviour, project its consequences and decide whether to maintain course, communicate, manoeuvre or take additional precautionary action. The interaction between these processes influences the safety and efficiency of the encounter. For this reason, mixed-traffic collision avoidance should be analysed not only through the performance of MASS collision-avoidance algorithms, but also through the conventional OOW's ability to perceive, understand, predict and trust MASS behaviour. Recent work similarly treats human–MASS interaction as an integrated process in which situational awareness, collision-avoidance decision-making

and trust jointly influence safety and efficiency in mixed traffic [32]. This study supports using the collision-avoidance framework not only to describe MASS functionality but also to analyse how the conventional OOW interprets and responds to autonomous behaviour.

The framework primarily represents collision avoidance during normal mixed-traffic operations and does not treat degraded or emergency response as a separate interaction domain. A normal encounter may nevertheless develop into a degraded or emergency situation as traffic conditions evolve, available time decreases, or relevant shipboard or supporting functions become unavailable. Across these conditions, the collision-avoidance processes are not necessarily completed fully, separately, or in a strict sequence. Perception, situation assessment, motion prediction, conflict detection, conflict resolution, and manoeuvre execution may develop iteratively and partly in parallel as the encounter evolves. Under degraded or emergency conditions, technical limitations or reduced time for intervention may compress these processes, change the allocation of functions between human and software agents, or require action before all stages have been completed. Such conditions therefore do not fall outside the framework. Instead, they may alter the timing, completeness, quality, and allocation of the processes represented within it.

Against this background, the presented framework helps to locate where specific mixed-traffic challenges may influence collision avoidance. Communication affects the information available for perception, situation assessment and motion prediction. The COLREGs and associated maritime practices shape expectations of vessel behaviour and guide conflict detection and resolution. Knowledge, training and preconceptions influence the mental models through which the OOW interprets MASS behaviour, while trust affects the extent to which the OOW is willing to rely on these interpretations when making and executing a decision. The following section uses the collision-prevention framework to examine these challenges from the perspective of the conventional OOW.

3. Mixed Traffic Navigation Challenges

Building on the collision-prevention framework developed in Section 2, this section shifts the analytical focus from the structure of the collision-avoidance process to the operational perspective of the conventional OOW. In mixed traffic, the OOW remains an active interaction partner who must interpret MASS behaviour, anticipate how an encounter may develop, and decide how to respond while retaining responsibility for the safe navigation of the conventional vessel. The following subsections therefore examine communication, COLREG interpretation, uncertainties surrounding MASS operations, and trust as challenges that may shape the OOW's understanding, expectations, and navigational actions during interaction with MASS.

3.1. Communication

During collision avoidance, communication serves three main purposes. First, it is used to broadcast information about a vessel's state and intentions, thereby increasing its predictability and allowing surrounding vessels to assess the situation and coordinate without explicit negotiation. Second, communication can provide additional information about a target vessel's intentions, supporting motion prediction. Third, vessels may use communication to coordinate or negotiate evasive manoeuvres, which in maritime practice may extend beyond a strict application of the COLREGs. Xiang et al. [14] argue that effective human-machine cooperation requires transparency not only about a system's final decisions, but also about its situational assessment, decision logic and planned actions. Applied to mixed-traffic communication, this suggests that MASS should provide sufficient information for the conventional OOW to understand its current state and navigational intentions. Viewed through the framework presented in Section 2, communication therefore

provides cues for observation and state estimation, supports motion prediction by clarifying intentions, and may shape conflict resolution through coordination.

MASS literature has revealed a strong need for further research regarding communication [27]. A recent study investigating challenges facing the regulatory process of MASS addressed the requirements for all ships to perform a permanent radio watch on the distress frequencies, to have the ability to send or relay emergency communication, and to use ship-to-ship contact. This study concluded that these communication protocols could remain mandatory and apply to MASS [52]. Alsos et al. [31] analysed the complete spectrum of maritime communication and found that current versions of MASS struggle to communicate their own intentions and perceive the intentions of other ships. Song et al. [53] further show that mixed-traffic interaction may occur without direct communication, with recognisable manoeuvring behaviour functioning as an implicit means of communicating intent to human operators. Conventional vessels and MASS will still need to communicate well into the foreseeable future to ensure safe navigational conduct [47,54].

Verbal communication via onboard radio remains the preferred method for vessel coordination and information exchange in traffic situations [55]. In a remote-control simulation involving a 4000-TEU containership, all 24 participants emphasised the need for direct voice contact with nearby vessels [56]. This highlights that voice communication remains essential, even in remote operations, and is reinforced by the COLREGs [55]. Verbal communication also has drawbacks, such as language barriers, inconsistent use of Standard Marine Communication Phrases [57], confusion between facts and interpretations, and static messaging that may overlook rapidly changing real-time conditions [55]. These challenges can lead to misunderstandings, confusion, and potentially dangerous situations at sea. Despite the challenges presented by voice communications, it remains an essential tool for sharing information and aiding collision avoidance.

Porathe and Rødseth [29] argued that future interactions between all vessels, including MASS and conventional vessels, can benefit from making intentions more transparent using e-navigation techniques such as route exchange. Building on the intended route exchange concept, Porathe et al. [58] proposed to aid collision avoidance and enhance navigational safety by only sharing a limited number of waypoints. This tactical route exchange was positively tested in a simulator study in which the concept was proven valuable to the 11 seafarers using it in various scenarios [58]. Questions do remain regarding route exchange techniques and their relation to enhancing navigational safety. For example, during the ACCSEAS project trials, using an integrated route exchange concept on the Electronic Chart Display and Information System (ECDIS), it was determined that displaying the “own ship’s” information with overlapping exchanged routes was confusing for the operators [59]. Similar results were found in other projects leading to the suggestion of having the ability to customise route exchange data on a need-to-know basis [59,60]. In addition to the potential information overload and clutter caused by exchanged routes, it is yet to be determined if the workload on the traditionally crewed vessel’s bridge would actually be reduced [58]. Also, the route exchange system’s ability to deal with changes within maritime real-world scenarios, which require vessels to change their course or speed, and with the incorporation of presented alternative routes, cause challenges for these e-navigation concepts [29]. Full Mission Bridge Simulator (FMBS) tests performed within the previously referenced STM validation project revealed that navigators breach the COLREGs more often when using route exchange technologies [60]. In contrast, navigational law violations are considered to be one of the root causes for collisions at sea. In conclusion, further research is therefore required to determine whether route-exchange concepts can reliably enhance collision avoidance without increasing workload, confusion, or inappropriate reliance on communicated routes.

During the STM validation project, the International Chamber of Shipping raised concerns that current navigational practices would be neglected and that overreliance and misinterpretation of route data could lead to potential false assumptions in the decision-making process of the OOW [60]. For example, OOWs could assume that the broadcast routes of target ships are the same as those ships' actual intentions while underway, which is incorrect, as vessels often do not follow routes exactly due to schedule, weather, traffic, and the motions of a vessel. At the same time, it remains unclear if route exchange technology would lead to vessels following their planned route to a greater extent [60]. Furthermore, Porathe and Rødseth [29] stated that for the route exchange to deliver precise data, a change in conventional ship behaviour is needed in which they adhere more strictly to their voyage plans. Both studies reflect the navigational reality in which plans and intentions communicated are not always executed. For example, the collision between the M/V CORVUS J and M/V BALTIC ACE was used by Hatlas-Sowinska and Wielgosz [55] to illustrate an incorrect use of communication in which the agreed-upon communicated plan was executed by different manoeuvres. Aside from human error in communication or execution of plans, there can also be cases in which the ship cannot execute the agreed-upon plan due to external circumstances such as equipment breakdown, weather conditions, etc.

Where such a failure or degraded condition materially affects the vessel's navigational capabilities, communication serves an additional safety function by making the resulting limitation apparent to surrounding vessels and other relevant traffic-management actors [21,52]. Conversely, a fault or degraded condition that can be accommodated without an externally relevant change in navigational capability does not necessarily require the same external response. The differences between a communicated message, a vessel's intention, and the actual execution of a vessel's plan should all be taken into account by the new communication technologies and protocols currently under development to further the evolution of MASS.

The literature reviewed in this section indicates that communication involving a human operator remains a critical and insufficiently understood aspect of MASS interaction. Communication failures, ambiguities, or inconsistencies between communicated intentions and executed behaviour may undermine the OOW's situational model and reduce the predictability required for effective conflict detection and resolution. However, it remains unclear which communication methods can most effectively support safe interaction with MASS and how conventional OOWs may adapt their communication practices in mixed traffic. These unresolved issues provide a basis for the research questions developed later in this paper.

3.2. COLREGs

The application of the COLREGs remains a crucial issue in the development and introduction of MASS [61]. Within the collision-avoidance process outlined in Section 2, the COLREGs do more than prescribe manoeuvres. They also provide a shared basis for anticipating other vessels' behaviour, thereby contributing to motion prediction, conflict detection, and conflict resolution. The recently adopted IMO MASS Code now explicitly requires autonomous and remote navigation systems to provide a means to take action in accordance with the COLREGs. It further requires collision-avoidance decisions to be timely, based on an assessment of risk, and not to create another situation presenting intolerable risk to the MASS, other ships or the marine environment [21]. Although this establishes the required regulatory outcome, it does not resolve how ambiguous and context-dependent COLREG provisions should be operationalised by MASS or how the resulting behaviour will be interpreted and reciprocated by conventional OOWs. Despite this regulatory requirement, a review of 79 scientific papers dealing with collision avoidance methods

for MASS revealed that, at best, these methods are only partly COLREG-compliant [62]. Huang et al. [44] outlined that collision avoidance algorithms need further development, particularly regarding target-motion prediction and the collaborative nature of collision avoidance. Additionally, the ambiguous nature of the COLREGs is difficult for MASS collision avoidance inference to deal with. Technical compliance therefore requires more than encoding individual rules. An autonomous navigation system must classify the encounter and associated vessel responsibilities, operationalise qualitative requirements such as “early and substantial action” and “safe distance”, and determine an appropriate response while accounting for uncertain or changing behaviour of surrounding vessels [44,62,63]. This is illustrated by the limited use of the right of way, as stipulated by the COLREGs, due to a lack of ability of MASS to interpret the intentions of other vessels [31]. To address this problem, Namazi and Perera [64] translate human navigational judgement into fuzzy decision rules for evaluating autonomous collision-avoidance behaviour, whereas Nguyen et al. [63] formalise selected COLREG requirements through Signal Temporal Logic and quantitative robustness metrics applied to pairwise AIS encounters. Together, these studies represent complementary approaches to COLREG assurance: one preserves interpretive flexibility, while the other prioritises measurable and machine-verifiable compliance. Nevertheless, both remain formal abstractions that cannot fully capture the contextual judgement through which an OOW determines whether a manoeuvre is timely, apparent, and appropriate in an evolving encounter.

These limitations may vary with the current mode of operation and the allocation of collision-avoidance functions between autonomous systems, remote operators, and onboard personnel. A transition between control configurations may change which human or automated actor assesses the encounter, selects the collision-avoidance response, and executes the resulting manoeuvre [22,35,36]. Regardless of this allocation, the resulting navigational behaviour remains subject to the COLREGs [21]. MASS collision avoidance algorithms must focus on more than just the COLREGs, since current collision avoidance systems do not include all potential traffic situations, including “black swan” events [56]. A study analysing the decisions made by OOWs onboard ferries in the Dover Strait revealed that aside from COLREGs, ships tend to follow informal rules out of practicality for the location [65]. More recently, Rutledal et al. [66] monitored the movement of ferries in Storfjorden, Norway, for 30 days and found that 13% of the identified collision evasive manoeuvres violated the COLREGs. These informal maritime practices are driven by environmental parameters, traffic density, the own vessel’s capabilities, and the need to remain in control of the situation, which may make such operational behaviour reasonable. MASS technology should take these maritime practices into account and have the ability to recognise these circumstances warranting deviations from the COLREGs when it wants to successfully interact with conventional vessels [66]. Madsen et al. [30] demonstrated a novel approach for mixed traffic situations in regional waters, considering the probabilities of deviations from the COLREGs based on historical data. These authors suggest that MASS could deviate from the COLREGs in a specified regional area if a conventional ship were expected to. MASS recognises rule violations as a potential failure mode [18]. The introduction of MASS may itself also influence how established maritime practices evolve. From the conventional OOW’s perspective, uncertainty about whether a MASS will follow the formal COLREGs, local navigational practices, or a system-specific interpretation may weaken the behavioural expectations used to predict the encounter and select an appropriate response. This regulatory and operational uncertainty forms part of the broader concerns surrounding MASS operations examined in the following section.

3.3. Operational Uncertainty and the OOW's Situational Model

From the conventional OOW's perspective, uncertainty surrounding MASS capabilities, operating modes, and behaviour becomes particularly important when it affects the construction and updating of the situational model. Surugiu et al. [20] describe MASS readiness as uneven across technological, regulatory, human-factor, and legacy-infrastructure dimensions, potentially increasing uncertainty for conventional OOWs. Against this background, the utilisation of autonomous systems within the maritime sector remains a subject of discussion amongst seafarers. Research indicates that crew members are amenable to the implementation of such systems, but they assert that they should be utilised as a supplementary tool, closely overseen by trained personnel, like an OOW, rather than serving as a substitute for them [67]. Various studies have shown that experienced seafarers strongly prefer human involvement in the decision-making process for MASS operations [54,68]. Although individual MASS functions may operate autonomously without continuous human intervention, the MASS Code requires human oversight and control and assigns responsibility to a human master regardless of the mode of operation [21]. However, the internal control configuration of a MASS is not directly observable to the conventional OOW. The OOW may not know the vessel's current mode of operation, the location of control, the available communication pathway, or how quickly human intervention can be provided. Detailed knowledge of the complete system architecture is not necessarily required. Rather, uncertainty about the operational configuration becomes relevant when it affects the predictability of the vessel, the means of communication, its manoeuvring behaviour, or the availability of human intervention. The OOW may therefore need to interpret and respond to MASS behaviour without a complete understanding of how the vessel is currently being controlled. Related concerns are also reflected in surveys of conventional OOWs. Hannaford et al. [61] found that 58% of participants preferred MASS to be separated from conventional traffic in congested areas through dedicated traffic lanes. These findings suggest that the "unmanned" aspect of MASS operations is causing the most unease among the seafaring community since the assumption that there will always be a human OOW available on the bridge of the other ships in traffic operations is now being questioned due to the implementation of MASS. The same study found that 85% of surveyed OOWs preferred a separate navigation light to indicate that a vessel was operating autonomously [61]. This desire to signal the level of autonomy (LOA) may reflect unease associated with reduced manning levels. A recent study reported that seafarers exhibit unease towards unmanned ships and believe that close observation of MASS may be necessary [54]. However, this heightened attention may lead to "attention tunnelling", whereby the OOW becomes fixated on the behaviour and performance of the MASS at the expense of other relevant information in the traffic environment. Within the framework presented in Section 2, such attention tunnelling may impair Level 1 situational awareness by causing the OOW to overlook relevant perceptual cues [50].

The MASS Code addresses human oversight, task allocation, safe manning, ROC watchkeeping, and operator competence, thereby reducing some regulatory uncertainty [21]. However, it does not specify what conventional OOWs need to know to interpret MASS operating modes, capabilities, or the availability of human intervention during an encounter. One could debate whether the current training of seafarers is sufficient to fully grasp the concept of autonomous shipping since it is difficult to fully understand the working principles of AI [69]. In addition, Hannaford and Van Hassel [70] reported concerns regarding the preparedness of deck officers and maritime training institutions for autonomous shipping. Recent research on MASS-related Maritime Education and Training confirms a readiness gap, but focuses mainly on personnel who operate or supervise MASS. Belabyad et al. [71] identified technical and digital proficiency, operational and managerial

competence, higher-order thinking and interpersonal skills as the principal competence categories discussed for the future MASS workforce. Similarly, Sharma et al. [72] assessed the STCW framework for personnel serving on degree-two MASS, while Emad and Ghosh [73] identify the skills and competencies required for future autonomous-ship operators and emphasise the need to align maritime training with changing human–automation roles. More recently, Campos et al. [74] implemented an introductory programme covering MASS, remote operation centres, human–automation interaction, cybersecurity and simulation. These studies generally retain conventional maritime competence as a baseline while supplementing it with automation-related knowledge. They do not, however, establish whether conventional OOWs encountering MASS as surrounding traffic require only basic familiarisation or a modified competence framework. Consequently, while some MASS-related knowledge appears necessary, the required depth, delivery method and implications for existing OOW training remain empirically unresolved. This uncertainty is becoming increasingly consequential as industrial development, operational trials and regulatory preparation for MASS continue to advance, while empirical research on how conventional OOWs understand and respond to these vessels remains limited. This emerging implementation–evidence gap risks widening the disparity between the mixed-traffic situations OOWs may encounter and the validated knowledge and training available to prepare them. Without an adequate knowledge base, OOWs may lack the basis needed to calibrate and update their mental models when observed MASS behaviour differs from prior expectations.

Another concern is the use of advanced sensors and AI to achieve higher levels of autonomy in shipping. The behaviour of autonomous agents, driven by advanced sensors and AI, is often difficult for humans to interpret. Their inability to explain their reasoning further hinders effective collaboration with human agents [26]. Greater explainability and transparency, for example through Explainable Artificial Intelligence (XAI) approaches, may therefore be needed to mitigate the ‘black box’ effect of MASS and facilitate collaboration between ships with different operational configurations. When the reasoning behind MASS behaviour remains opaque, the OOW may perceive the vessel’s actions without being able to comprehend why they occur, creating a Level 2 situational-awareness problem.

The drive to enhance or surpass human decision-making by technology causes the MASS systems to build situational awareness over a larger area than humans. This difference in lookout horizons can cause MASS to perform manoeuvres based on targets or conflicts that the surrounding conventional ships did not yet consider. This so-called “automation surprise” was already reported by [26]. Automation surprise may therefore disrupt Level 3 situational awareness because unexpected MASS actions make it more difficult for the OOW to project how the encounter will develop. The importance of the predictability of MASS to seafarers on conventional ships was also highlighted by [54]. Automation surprise may also trigger responses from the conventional ship that a MASS trained on historical data interprets as unconventional, further complicating navigation in mixed traffic.

It can be difficult to understand the true capabilities of an autonomous ship system. It is important to consider the perceived level of autonomy (LOA) instead of just the theoretical LOA. Given the uncertainties surrounding MASS implementation and the lack of specific training, OOWs may attribute capabilities to autonomous ship systems that they do not possess. This mismatch may be reinforced by the image of innovation created by promotional discourse surrounding MASS [69]. A discrepancy between perceived and actual autonomy may therefore cause the OOW to apply an inappropriate mental model and attribute unrealistic capabilities or intentions to the MASS. Such a mental model may lead to the misinterpretation of information and impair the OOW’s ability to

maintain situational awareness [50]. Decisions based on incorrect assumptions about MASS technology may be particularly dangerous in mixed-traffic environments.

In summary, operational uncertainty may affect the OOW's situational model at several stages of the collision-avoidance process. Heightened attention to MASS may narrow Level 1 perception, opaque behaviour may impede Level 2 comprehension, and automation surprise may undermine Level 3 projection. Knowledge and training gaps, together with incorrect perceptions of autonomy, may further hinder OOWs from calibrating the mental models used to interpret MASS capabilities and behaviour. These effects may also influence whether MASS behaviour is perceived as sufficiently predictable and reliable, linking operational uncertainty to the trust issues examined in the following section.

3.4. Trust

The avoidance of collisions at sea heavily depends on trust and the willingness to take risks. This is because effective and safe vessel manoeuvres require trust between ships [54]. Trust should therefore be treated as a cross-cutting influence on how the OOW weighs information, relies on predicted MASS behaviour, and determines the threshold and timing for intervention and manoeuvre execution. Mayer et al. [75] noted that trust is essential in risky situations and involves some level of vulnerability. According to Mayer et al. [75], trust is the willingness to be vulnerable to the actions of another based on the expectation that they will perform an action important to the trusting party, regardless of their ability to monitor or control the other party.

In the context of mixed-traffic navigation, the importance of trust is likely to be even more significant. Research has shown that for collaboration between empowered workers in self-directed teams, the importance of trust increases when the control mechanisms are reduced, and the interaction increases [76]. When the level of autonomy increases while human control simultaneously decreases, the trust between vessels becomes more critical when they interact with each other.

When examining this trust from the conventional ships' OOW point of view in a mixed traffic scenario, both the OOW's propensity to trust and the trustworthiness of the MASS need to be considered as specified in the integrative model of trust by [75]. To interpret the perceived trustworthiness of MASS, we consider the three nodes identified in the integrative model of Mayer et al. [75]: first, the perceived skills and expertise of the trustee (ability); second, the belief that the trustee intends to do good for the trustor (benevolence); and finally, the trustee adheres to a set of principles that is acceptable to the trustor (integrity).

In the previous section, we identified a gap in the knowledge of the OOWs concerning the capabilities of MASS in collision avoidance scenarios. As a result, it is difficult for the OOW to examine MASS capabilities. As indicated previously, there are already concerns regarding predicting the intentions of other ships in both mixed and conventional shipping environments. For instance, the most cited phrase in VHF communication during collision avoidance in conventional scenarios is: "What are your intentions?" Additionally, there are also questions about how MASS will deal with the important principles of operations at sea, such as the COLREGs, since there is a gap in the legal framework and ambiguity concerning the responsibilities and liabilities in autonomous shipping. Hynnekleiv and Lützhöft [69] identified trust-related challenges regarding the trustworthiness of MASS, such as the transition between operational modes in MASS, the lack of transparency in the functioning of MASS, and the difference between perceived autonomy and realised autonomy. Importantly, these uncertainties may not only produce distrust; apparently precise or authoritative system outputs may also encourage OOWs to place more confidence in MASS behaviour than is warranted. Leonardi et al. [77] describe this effect as "artificial certainty":

the tendency of concrete and apparently comprehensive AI-generated representations to make uncertain outcomes appear more knowable than they actually are. Applied to mixed-traffic navigation, the apparent precision of MASS decisions or communicated outputs may therefore cause OOWs to overestimate system reliability, reinforcing inaccurate mental models and poorly calibrated trust.

The lack of previous experiences of ships interacting with MASS leads to the absence of history-based trust in mixed traffic navigation. As a result, the OOWs' propensity to trust may depend strongly on the operator's personal traits and prior knowledge. There may be challenges regarding the OOW's propensity to trust MASS during collision avoidance, since the OOW's preconceptions, willingness to interact with and mental models of MASS operations still need to be researched. Chan et al. [67] noted that besides challenges such as potential job insecurity and bias towards the system, OOWs were confident in trusting autonomous systems provided they were suitably trained in using them. The necessary training still needs to be investigated and developed. Doroftei et al. [78] described the importance of the operators' communities' socio-ethical value systems on both the perceived trustworthiness of MASS and on the OOWs' propensity to trust. The limited historical experience with MASS at sea, along with previously identified knowledge and training deficiencies, may profoundly affect key social and ethical values, potentially undermining trust in mixed-traffic maritime environments. In conclusion, trust is vital for ships to achieve efficient, effective, and safe collision avoidance. However, to establish trust in mixed-traffic collision avoidance, there could be issues with both the propensity of the OOW and the trustworthiness of MASS. This could have far-reaching consequences for the safety and sustainability of mixed maritime transportation systems, making it imperative to address these challenges proactively. It is necessary to identify and address the gaps in knowledge and training related to the interaction with MASS. It is also important to investigate the willingness of participants to engage with this technology and analyse the personal factors that influence the OOW's inclination. This will help to build trust and confidence in the use of MASS technology in mixed traffic environments.

Viewed through the collision-avoidance framework, the four challenge areas examined across Section 3 are closely interconnected. Communication and COLREG interpretation provide information and behavioural expectations, while operational uncertainty and trust influence how these inputs are interpreted and weighted by the OOW. Together, they may affect the construction of the situational model, the prediction of MASS behaviour, the detection and resolution of conflicts, and ultimately the manoeuvres executed by the conventional vessel. These interdependencies provide the basis for the research questions developed in the following section.

4. Discussion and Future Research

4.1. Integrated Interpretation of the Findings

Our paper set out to assess mixed-traffic navigation from the perspective of a conventional ship's OOW and, more specifically, to investigate how OOW behaviour might change due to the introduction of MASS. The preceding analysis suggests that MASS should not merely be regarded as a new category of target vessel within the maritime traffic environment. The collision-avoidance framework highlighted the importance of accurate and reliable collision-avoidance processes for maintaining navigational safety and showed that motion prediction is essential for determining collision risk and achieving effective and safe collision prevention in mixed-traffic environments. However, motion prediction remains particularly challenging because collision avoidance between autonomous and conventional vessels is an iterative and dynamic process in which predictions must account for surrounding-vessel behaviour and interaction features [44,53]. The ability to project the

future development of a situation is equally crucial for the human OOW, who must build an accurate situational model to detect and resolve collision risks in a timely manner [50]. Interaction with MASS may affect how the conventional OOW observes the traffic situation, interprets the behaviour and intentions of other vessels, predicts their future states, and determines whether, when, and how to intervene. Communication limitations, uncertainty regarding MASS capabilities and operational behaviour, COLREG interpretation, mental models, and trust should therefore not be regarded as isolated challenges. Instead, they interact throughout the collision-avoidance process and may ultimately influence the timing, type, and execution of the conventional vessel's manoeuvres.

This interactional perspective is also relevant when considering the anticipated reliability benefits of MASS. Increased automation may reduce some bridge-level operational errors, but it does not necessarily remove the influence of human factors from the navigational system. As navigational functions are increasingly allocated to autonomous systems, remote operators and shore-based support, human roles shift from direct ship control towards supervision, intervention, mode management and human-machine-shore collaboration. Recent research suggests that this transition may introduce different human-factor risks related to supervisory cognition, trust in automation, mode transitions, takeover and coordination between human and automated actors [9–11]. Consequently, the reliability of MASS should not be considered solely in terms of the reduction in onboard human involvement. Furthermore, reliable performance of the MASS itself does not necessarily ensure safe interaction in mixed traffic. A MASS may operate as intended while its manoeuvring behaviour, timing or communicated intentions are interpreted differently by a conventional OOW. Safe mixed-traffic operation therefore depends not only on the performance of the MASS, but also on how its behaviour is perceived, understood and anticipated by conventional OOWs.

The central unresolved issue is consequently whether, how, and under which operational conditions interaction with MASS changes the collision-avoidance behaviour of conventional OOWs. Importantly, these questions do not depend on the occurrence of a technical failure. The MASS Code requires autonomous and remote navigation systems to support safe operation and to provide a means to take action in accordance with the COLREGs [21]. However, these requirements do not remove the uncertainty surrounding mixed-traffic interaction. The human-factor issues identified in this paper may therefore occur during normal mixed-traffic operations and are not limited to degraded or emergency conditions. Although the literature identifies multiple technical, regulatory, and human-factor challenges, there remains limited empirical evidence concerning how these factors jointly affect the conventional vessel as an active interaction partner. The collision-avoidance framework presented in this paper provides an analytical lens through which these challenges can be related to the different stages of observation, situational awareness, motion prediction, conflict detection, conflict resolution, and manoeuvre execution. This interpretation is consistent with the integrated human-MASS interaction framework proposed by Song et al. [32], which connects situational awareness, decision-making in mixed waterborne transport systems, and human trust. The present paper complements this perspective by positioning the conventional OOW as an active external interaction partner and tracing these factors through the reactive collision-avoidance process. Within this process, the impact of the situational model on collision prevention in mixed environments cannot be overlooked, especially the role of the OOW's mental models. These thought processes may differ from those used in traditional navigation environments and may influence how the OOW interprets the behaviour and intentions of MASS, predicts the future development of the traffic situation, and determines whether, when, and how to

intervene. Future work is therefore required to investigate how the OOW's mental models and overall situational model might be affected by the introduction of MASS at sea.

The third section identified the main challenges of navigating in a mixed-traffic environment and examined how they may affect the collision-avoidance process described by the framework. Challenges were identified in the communication methods required between MASS and conventional ships. Current versions of MASS have limited communication capabilities, particularly concerning communication methods that currently involve direct human control, such as VHF voice communication [31]. It therefore remains unclear which methods would be most effective for establishing the necessary communication and coordination with MASS. This uncertainty may influence the information available to the OOW and consequently affect observation, situational awareness, motion prediction, and conflict resolution. Additional concerns arise from the interpretation and application of the COLREGs during interactions between MASS and conventional ships. Although the recently adopted non-mandatory MASS Code provides an initial goal-based framework for the safe integration of autonomous and remotely operated ships, it does not remove the need to investigate how the COLREGs will be interpreted and applied during mixed-traffic encounters [21]. Furthermore, seafarers' current knowledge gaps and concerns regarding the capabilities, development, and operation of MASS may challenge the OOW's situational awareness and mental models when navigating in mixed environments. There may also be issues concerning both the OOW's propensity to trust and the perceived trustworthiness of MASS, potentially undermining the trust required between vessels to perform safe and effective collision-avoidance manoeuvres. Taken together, these findings indicate that communication, COLREG interpretation, MASS knowledge, mental models, and trust do not influence collision avoidance independently. They affect the information available to the OOW, the construction and projection of the situational model, and the subsequent detection and resolution of a conflict. By locating these influences within the successive stages of the collision-avoidance framework, the framework provides a structured analytical lens for relating mixed-traffic challenges to observable changes in OOW decision-making and manoeuvre execution. However, the direction and magnitude of these effects, and the operational conditions under which they occur, remain insufficiently understood. These unresolved questions have practical implications for conventional OOW training, MASS development and operation, and mixed-traffic safety assurance, although the appropriate form and extent of the required interventions cannot yet be fully specified. Section 4.2 therefore outlines the preliminary implications that can already be drawn and the empirical evidence still required, while Section 4.3 translates the remaining behavioural, interactional and operational uncertainties into a structured research agenda.

4.2. Practical Implications for Mixed-Traffic Integration

The findings presented in this review suggest several immediate but necessarily provisional directions for conventional OOW training, the development and operation of MASS, and the safety assurance of mixed-traffic operations. Some measures can already be initiated, whereas formal training requirements, design choices and approval criteria should be guided by further empirical evidence.

4.2.1. Training Implications

The analysis in Section 3 identified a specific gap in current MASS-related Maritime Education and Training. Existing studies mainly address personnel who operate, supervise or remotely control MASS, while the preparation of conventional OOWs who will encounter these vessels in mixed traffic remains largely unexamined. Sharma et al. [72], Emad and Ghosh [73], Campos et al. [74] and Belabyad et al. [79] generally retain con-

ventional maritime competence as an important foundation while proposing additional digital, operational and human–automation knowledge for the future MASS workforce. However, these studies do not establish what conventional OOWs need to know, how extensively they should be trained, or whether interaction with MASS requires a separate competence framework. The knowledge and preparedness concerns identified in Section 3 should therefore not be interpreted as evidence that existing navigational training must be fundamentally redesigned.

Existing competencies in watchkeeping, COLREG application, communication, shiphandling and situational awareness should remain the baseline. Whether additional learning outcomes are required will depend on how different MASS configurations are implemented in practice, including their control arrangements, functional allocation, human oversight, communication architecture, operational envelope, fallback arrangements and externally observable behaviour. A staged approach is therefore appropriate. First, the immediate knowledge gap can already be addressed through proportionate technical familiarisation embedded within existing navigational education. Conventional OOWs should develop a basic understanding of MASS concepts, remote operation centres, control arrangements, communication availability, relevant system limitations, mode transitions and the operational consequences of degraded operation or loss of connectivity. The purpose is not to prepare them to operate or troubleshoot MASS, but to support realistic expectations, calibrated trust and more accurate mental models of the capabilities and limitations of these vessels.

Second, the research agenda outlined in Section 4.3 and the FMBS approach described in Section 5 should determine whether, and under which conditions, interaction with MASS produces operationally relevant changes in OOW attention, communication, COLREG application, situational awareness, trust or collision-avoidance behaviour. These findings can guide the required depth of familiarisation and indicate whether additional learning outcomes or competence adaptations are justified. At the same time, different MASS configurations could already be introduced on an exploratory basis into existing bridge-simulator exercises. Because mixed traffic is expected to become a persistent operational condition rather than a separate navigational domain, remotely controlled and autonomous vessels should progressively be represented within the same crossing, head-on, overtaking, restricted-water and multi-ship scenarios used for other traffic participants. This would allow conventional OOWs to encounter MASS as part of the normal traffic environment while retaining established learning objectives for watchkeeping, communication, COLREG application and collision avoidance. Treating MASS exclusively within separate courses could unintentionally reinforce its perception as an exceptional vessel category and encourage rigid expectations based on autonomy labels rather than mental models that are continuously updated through observed behaviour, communication and navigational context. The effectiveness of this integrated approach, including the MASS characteristics that should be represented in training scenarios, should nevertheless be evaluated through simulator research. Formal curriculum or competence requirements should remain adaptive and follow empirical validation rather than precede it.

4.2.2. Industry and System-Design Implications

The findings also have implications for the development and operation of MASS. Current human-centred design approaches largely focus on the people who operate, supervise or remotely control the autonomous vessel [13,14]. However, the conventional OOW is also part of the wider sociotechnical system in which MASS will operate. MASS should therefore not only perform collision avoidance safely according to its own sensors, decision processes and regulatory logic, but should also behave in a way that nearby conventional

OOWs can interpret within the time available [14,31,54]. This places particular importance on the external predictability of manoeuvres, the consistency between communicated intentions and executed actions, the availability of appropriate communication channels, and the recognisability of mode transitions, fallback behaviour and degraded operation [22,47]. These characteristics cannot be evaluated through technical performance alone, since a technically correct manoeuvre may still create uncertainty or trigger unnecessary intervention on the conventional bridge. MASS developers and operators should therefore include conventional OOWs in the iterative design and validation of communication concepts, manoeuvring strategies, operating-mode transitions and fallback arrangements for mixed-traffic environments.

COLREG compliance should remain a fundamental design and validation requirement, but compliance alone may not ensure that MASS behaviour is sufficiently clear or predictable when the Rules allow contextual interpretation or when surrounding vessels act unexpectedly [44,62,65,66]. Although historical traffic data provide a valuable basis for modelling manoeuvring patterns and navigational preferences [30,44,53], they may not capture how conventional OOWs adapt their communication, expectations and collision-avoidance behaviour when interacting with MASS. The resulting interaction patterns may therefore not be represented in existing datasets, and development and validation should not rely on these data alone. Human-in-the-loop FMBS experiments involving conventional OOWs are needed to compare candidate communication technologies, manoeuvring strategies and system responses [80,81]. Closer engagement and greater transparency between MASS developers, operators, maritime training institutions and seafaring communities could support this process by improving understanding of emerging capabilities and limitations, identifying practical training and policy needs, and facilitating the participation of experienced OOWs in simulator-based validation. The resulting evidence could inform system requirements, the Concept of Operations and operational guidance, while final design choices should remain dependent on the intended operational envelope and mixed-traffic context.

4.2.3. Policy and Safety-Assurance Implications

The same interaction evidence is also relevant to the approval and safety assurance of MASS operating in mixed traffic. The MASS Code establishes safe coexistence between MASS and conventional ships as a regulatory objective and requires the approval process to consider the Concept of Operations, operational envelope, modes of operation and anticipated traffic conditions [21]. However, the Code does not specify how the effects of MASS behaviour on conventional OOWs should be evaluated. Without such evaluation, approval processes may treat the behaviour of conventional OOWs as an unchanged boundary condition, although the introduction of MASS may affect their situational awareness, communication, expectations, trust and collision-avoidance decisions. Bolbot et al. [82] argue that MASS safety acceptance requires a goal-based and sociotechnical approach that extends beyond technical performance or equivalence with conventional ships. Corsi et al. [83] similarly propose a risk-informed certification process in which verification and validation are adapted to the intended operational context and associated risks. Building on these approaches, the principal policy implication of this review is that the MASS Code's objective of safe coexistence should be explicitly included in MASS safety assurance by evaluating how MASS behaviour affects conventional OOWs in the intended mixed-traffic environment. COLREG compliance should remain an important regulatory baseline, but should not be the only validation criterion. Evaluation should also determine whether MASS behaviour remains sufficiently predictable during ambiguous encounters,

non-compliant behaviour by surrounding vessels and transitions between operating modes, and whether it may cause potentially unsafe adaptations by conventional OOWs.

Further research is required to determine how this human-centred extension can be translated into practical validation and certification requirements. The scenario-based FMBS approach described in Section 5 could provide an initial step by investigating interactions under different operating modes, traffic conditions and system states. Normal operations should be studied first, followed by degraded and fallback conditions that may change the behaviour or predictability of the MASS. The results could then be used to define measurable functional requirements for safe interaction, including whether operationally relevant information is understandable, available in time and sufficient to support the OOW's decision-making. Candidate solutions, such as VHF communication, digital route exchange or distinct lights and shapes, should be compared empirically instead of being prescribed before their effects on conventional OOWs are understood.

Once simulator studies have identified acceptable behaviour and relevant boundary conditions, these findings should be examined through controlled operational trials and subsequently through limited deployment with monitoring and feedback. The resulting evidence could be used to refine the Concept of Operations, operational envelope, approval conditions and associated guidance. Throughout this process, collision-avoidance decisions, changes in operating mode and relevant system data should remain reconstructable and sufficiently explainable to support safety evaluation, accident investigation and learning from operational experience [84]. Together, these implications identify where the conventional-OOW perspective should inform mixed-traffic integration, while also showing where the available evidence remains insufficient to define definitive training, design or approval requirements. They should therefore be understood as preliminary, evidence-dependent directions rather than fixed prescriptions. The research questions in Section 4.3 address the underlying behavioural and operational uncertainties concerning how interaction with MASS affects conventional OOW behaviour and decision-making. The resulting evidence can then be used to further specify and validate the measures outlined above.

4.3. Future Research

The following research questions translate the empirical gaps identified in the preceding analysis into a structured agenda for investigating how interaction with MASS may affect the conventional OOW throughout the collision-avoidance process. In addition to advancing understanding of mixed-traffic interaction, the resulting evidence could inform the training, system-design and safety-assurance directions outlined in Section 4.2. The questions progress from observable collision-avoidance behaviour and its underlying cognitive processes to communication, COLREG application, watchkeeping performance, and the operational conditions under which these effects may occur. Although presented together, they are not intended to be addressed within a single experiment. Instead, they provide a structured basis for a series of scenario-driven studies.

4.3.1. Collision-Avoidance Behaviour and Cognitive Processes

- RQ1. How does interaction with MASS, compared with interaction with conventionally crewed vessels, affect the timing, type, and execution of collision-avoidance manoeuvres by OOWs?
- RQ2. How do OOW experience, prior knowledge of MASS, targeted familiarisation and propensity to trust influence the mental models used to construct and project the situational model during interaction with MASS?

- RQ3. How does the presence of MASS influence how OOWs use and integrate navigational information from visual observations, radar, AIS, and ECDIS when assessing the traffic situation?

4.3.2. Communication and Coordination

- RQ4. How do the frequency, timing, and type of communications initiated by OOWs differ between encounters with MASS and encounters with conventionally crewed vessels?
- RQ5. How do different verbal, non-verbal and digital communication modalities, including VHF, AIS and route or intention exchange, affect OOW comprehension and coordination, and what patterns emerge in their selection and use?
- RQ6. How does interaction with MASS, compared with interaction with conventionally crewed vessels, affect OOWs' reliance on course and speed changes as implicit communication cues and their interpretation of and response to inconsistencies between communicated intentions and executed manoeuvres?

4.3.3. COLREG Application and Watchkeeping

- RQ7. How does interaction with MASS affect OOWs' interpretation and application of the COLREGs, particularly when MASS behaviour is ambiguous, unexpected, or perceived as non-compliant?
- RQ8. How does interaction with MASS affect the OOW's ability to maintain a safe navigational watch, as reflected in situational awareness, workload, decision latency, and navigational performance?

4.3.4. Operational Context and MASS Configuration

- RQ9. How do operational conditions, including navigational area, traffic density, and visibility, moderate OOW behaviour and decision-making during interactions with MASS?
- RQ10. How do MASS control arrangements, operating modes, mode transitions and degraded or fallback conditions affect the predictability and perceived trustworthiness of MASS behaviour and the responses of conventional OOWs?

These research questions can be operationalised through controlled and reproducible mixed-traffic scenarios. The following section outlines how FMBS can translate them into scenario factors, participant variables, and corresponding behavioural and human-factor measurements.

5. Leveraging Full Mission Bridge Simulators for Mixed Traffic Research

Full mission bridge simulators (FMBS) are beneficial for navigational research as they allow for flexible, real-time, and reproducible scenarios [85]. Therefore, FMBS provide a means of operationalising these research questions by exposing OOWs to controlled and reproducible mixed-traffic encounters while preserving the complexity of bridge operations, vessel dynamics, navigational instruments, and traffic interaction. They are also a valuable tool for analysing navigational safety [86], navigational risk [87], navigator competence [88], and conducting mixed traffic research [80]. Recent uses of ship simulators in nautical research include search and rescue operations [89] ship manoeuvrability [90], collision-risk mitigation analysis [91], measurement of a navigator's mental workload [92], wearable augmented-reality display technology [93], and operator-stress assessment [94]; simulators have also been recommended for understanding and evaluating autonomous ship algorithms [95]. FMBS therefore provide an appropriate test environment for examin-

ing both observable collision-avoidance behaviour and underlying human-factor constructs such as situational awareness, workload, mental models, communication, and trust.

FMBS are likely to be effective, efficient, and reliable test beds for investigating autonomous shipping and mixed traffic scenarios. For example, Bonser [81] proposed a standard test method using FMBS to analyse the safety and reliability of autonomous navigation systems. This methodological role is further reinforced by the MASS Code, which incorporates simulation into the approval, verification, and validation process for MASS systems [21]. However, these provisions primarily concern the MASS, associated ROCs, and remote operators, and do not explicitly address how conventional OOWs respond to MASS behaviour in mixed traffic. Such experiments can be used to evaluate changes in OOW behaviour and decision-making, including situational awareness, communication practices, COLREG application, workload, and trust during interactions with MASS. Building on this methodological potential, Table 1 translates the research questions identified in the previous section into illustrative scenario factors, participant characteristics, and corresponding outcome measures.

Table 1. Illustrative operationalisation of the research questions through scenario-driven FMBS studies.

RQ	Research Focus	Experimental Factors, Scenario Parameters, and Example Conditions	Potential Measurements
RQ1	Collision-avoidance behaviour and manoeuvre execution	Target-vessel type: conventional vessel or MASS; MASS behaviour: predictable, COLREG-compliant, ambiguous, or unexpected	Time of first intervention; decision latency; course and speed alterations; manoeuvre magnitude; CPA/TCPA; encounter outcome
RQ2	Mental models, situational awareness, and trust	OOW experience; prior MASS knowledge or exposure; MASS training; propensity to trust	Prediction accuracy; SAGAT/SART; trust ratings; perceived predictability; semi-structured interviews; mental-model elicitation
RQ3	Observation and integration of navigational information	Target-vessel type; availability and consistency of visual, radar, AIS, and ECDIS information	Instrument use; information cross-checking; eye-tracking; display interactions; detection accuracy; SAGAT responses
RQ4	Explicit communication and coordination	Target-vessel type; VHF availability; responsive or non-responsive target vessel	Number, timing, duration, and content of communication attempts; response rate; coordination success
RQ5	Selection of communication modalities	No direct communication; VHF; AIS messaging; route or intention exchange; combinations of modalities	Selected modality; switching between modalities; response time; communication errors; misunderstandings; perceived usefulness
RQ6	Implicit communication through vessel behaviour	Availability of explicit communication; early, late, ambiguous, or absent course and speed alterations	Detection and interpretation of manoeuvring cues; reliance on course and speed; prediction accuracy; own-ship response time; interview data

Table 1. Cont.

RQ	Research Focus	Experimental Factors, Scenario Parameters, and Example Conditions	Potential Measurements
RQ7	COLREG interpretation and application	Encounter type: crossing, head-on, or overtaking; MASS behaviour: compliant, ambiguous, unexpected, or non-compliant	Identification of the applicable COLREG rule; stand-on or give-way behaviour; timing and type of manoeuvre; rule deviations; perceived predictability
RQ8	Situational awareness, workload, and safe watchkeeping	Target-vessel type; scenario complexity; predictable or uncertain MASS behaviour	NASA-TLX; SAGAT/SART; decision latency; missed targets or information; CPA/TCPA; navigational errors; eye-tracking indicators
RQ9	Operational context as a moderating factor	Navigational area; traffic density; visibility; weather; day or night conditions	Effects on the behavioural and human-factor measurements associated with RQ1–RQ8
RQ10	MASS configuration and operational condition	MASS control arrangement: autonomous, remote, or combined; operating mode: stable or transitioning; operational condition: normal, degraded, or fallback	Effects on the behavioural and human-factor measurements associated with RQ1–RQ8

Experimental factors refer to variables deliberately manipulated to examine a specific relationship, whereas scenario parameters describe contextual conditions that may be controlled or systematically varied depending on the purpose of the study. Example conditions illustrate possible operationalisations of these factors and parameters within an FMBS scenario. For example, in a study of COLREG application, encounter type may be treated as an experimental factor, visibility as a scenario parameter, and a crossing encounter under restricted visibility as an example condition. The proposed factors and parameters should not all be incorporated into a single experimental design. Instead, individual studies should select a limited combination of experimental factors, scenario parameters, participant characteristics, and measurements according to the research question under investigation. Initial studies should establish baseline OOW behaviour during normal encounters with predictable and COLREG-compliant MASS behaviour, after which ambiguous behaviour, degraded operation, or emergency conditions can be introduced as controlled extensions.

Operational conditions such as navigational area, traffic density, visibility, weather conditions, waterway constraints, and regional navigation practices should therefore be treated as contextual or moderating variables where relevant. Traffic density can, for example, be varied through the number and proximity of surrounding vessels, encounter frequency, and the proportion of conventional vessels and MASS. Weather and visibility can be controlled through predefined visibility ranges, sea states, wind conditions, or precipitation, while navigational area can be represented through open-water, coastal, narrow-channel, or port scenarios with corresponding differences in manoeuvring space and navigational constraints. Regional navigation practices may be represented through traffic organisation, reporting requirements, VHF conventions, pilotage arrangements, or routing measures. These conditions should either be held constant when another relationship is being isolated or systematically varied when their moderating effect forms part of the research question.

For studies addressing RQ10, the MASS mode of operation, allocation of navigational functions, mode transitions, and degraded or fallback conditions may be included as scenario factors, provided that the relevant operational condition or configuration is either known to the participant or results in controlled differences that are externally observable during the encounter. Studies addressing RQ4–RQ6 may focus on communication availability and modality, whereas studies addressing RQ7 may manipulate encounter type and the predictability or COLREG compliance of MASS behaviour. The operational conditions identified under RQ9 can be included as moderating factors.

The measurements in Table 1 combine objective simulator data, such as manoeuvre timing, course and speed alterations, CPA/TCPA, communication attempts, and instrument use, with human-factor measures. NASA-TLX can be used to assess workload, while SAGAT or SART can measure situational awareness. Trust ratings and semi-structured interviews can further explore participants' mental models, perceived MASS trustworthiness, understanding of system behaviour, and reasons for particular decisions. Eye-tracking and physiological measures, such as galvanic skin response or heart-rate variability, may provide additional insight into visual attention and stress but should only be included when directly relevant to the research question.

Figure 3 combines these elements in a modular FMBS experimental protocol. The protocol includes participant profiling, a pre-experiment briefing, one or more mixed-traffic scenarios, continuous recording of behavioural and simulator data, and post-scenario measurements and debriefing. It is not intended as a fixed experimental design, but as an adaptable workflow through which the variables and measurements identified in Table 1 can be combined according to the objectives of an individual study.

FMBS also have limitations that should be considered when interpreting the resulting evidence. Although they provide a controlled and reproducible environment and allow situations to be tested that would be difficult or undesirable to reproduce at sea, they remain a representation of real mixed-traffic operations. The accuracy required from a simulator and its underlying manoeuvring models depends on the intended application, and differences between simulator models may become particularly relevant under changing environmental conditions [85,90]. Harrington et al. [96] recently examined scenario-design practices in maritime simulator training and assessment and identified realism, authenticity and fidelity as important considerations when relating a simulated scenario to professional practice. Rather than requiring every element of a scenario to reproduce reality in equal detail, they emphasise functional congruence between the simulated situation and the real-world activity being represented. Although their study concerns training and assessment, this consideration is also relevant to FMBS research. The validity of a mixed-traffic experiment therefore depends not only on simulator fidelity, but also on the assumptions made during scenario design and on how MASS behaviour, communication arrangements, surrounding traffic and operational conditions are represented. Participants may also behave differently because they are aware that they are operating in an experimental environment without the same operational consequences as at sea. Furthermore, no individual scenario can reproduce the complete variation in traffic, environmental conditions, regional navigation practices, vessel configurations and human behaviour encountered during real operations. Findings from an individual FMBS study should therefore not be assumed to generalise directly to all mixed-traffic situations.

A further limitation concerns the practical scale of FMBS research. Ship-bridge simulator research requires access to suitable simulator infrastructure, participants, technical support and maritime expertise [85]. This becomes particularly relevant when experiments require licenced and appropriately experienced OOWs, whose availability may limit the number of participants that can be included. Relatively small sample sizes may conse-

quently limit the statistical power and generalisability of individual studies. At the same time, because the resulting evidence depends strongly on the assumptions and scenario design preceding the experiment, scenario development should involve experienced OOWs and relevant MASS experts and should be tested before the main experiment. This is particularly important where the behaviour or capabilities of the simulated MASS are not yet established through operational experience. The targeted and modular approach proposed above partly addresses these limitations by restricting individual studies to a limited number of experimental factors and scenario parameters and by first establishing baseline behaviour before more complex conditions are introduced. FMBS should therefore be considered an initial controlled stage of empirical investigation rather than a complete validation of the proposed framework or of safe MASS interaction. Findings should be replicated across different scenarios and participant groups and, where feasible, subsequently examined through controlled operational trials and monitored deployment.

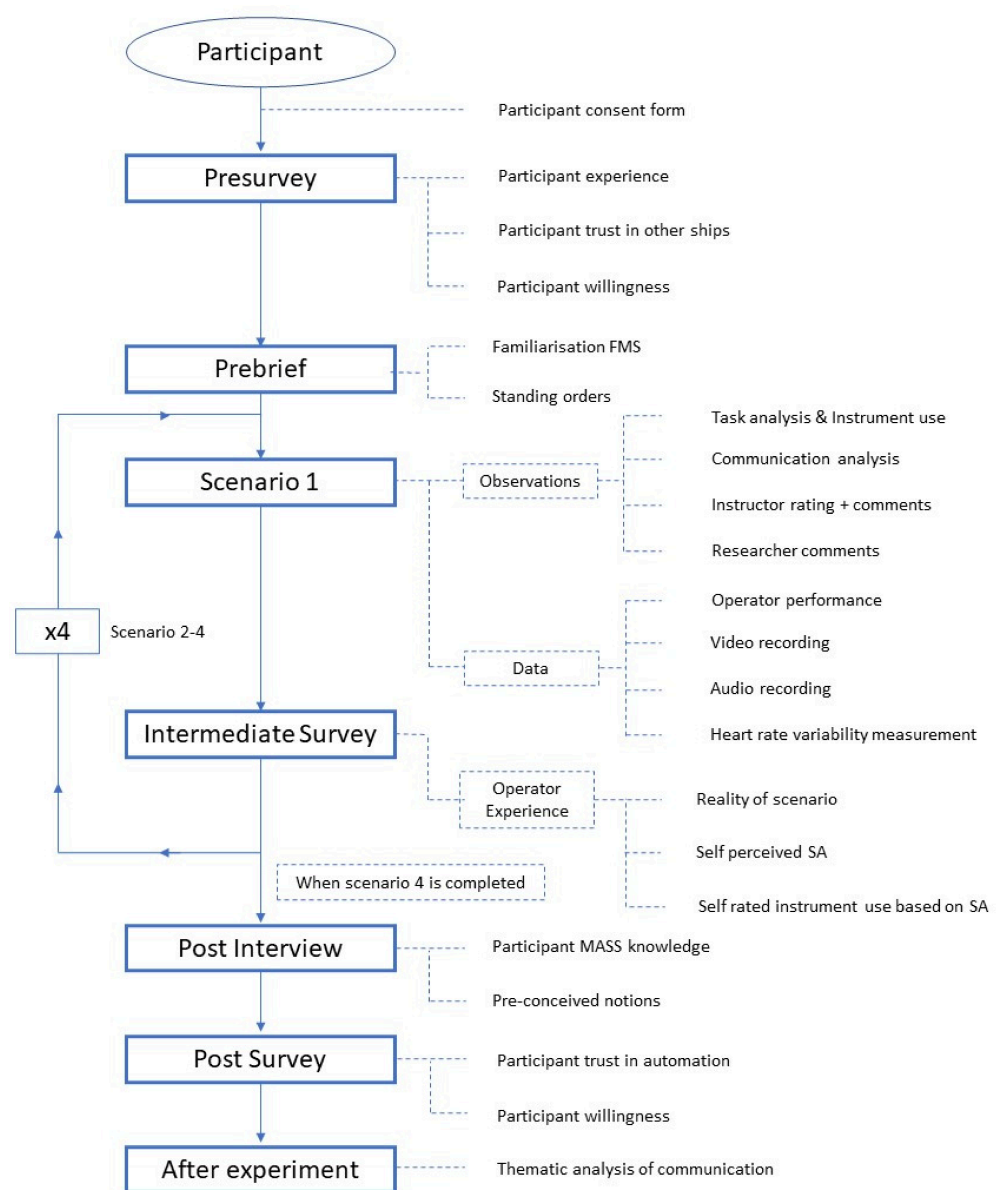


Figure 3. Sketch of a full mission bridge simulation experiment protocol for investigating conventional OOW interaction with MASS.

Despite these limitations, FMBS remain particularly suitable for the research questions proposed in this paper. They allow MASS behaviour, communication arrangements,

encounter characteristics and operational conditions to be systematically manipulated while preserving realistic bridge tasks and recording both behavioural and human-factor responses. Baseline OOW behaviour can therefore first be established during normal encounters under controlled and reproducible conditions. More demanding situations, including close-quarters encounters, unexpected manoeuvres or degraded conditions, can then be introduced safely as controlled extensions. Such situations would be difficult to investigate at sea with the same level of control, reproducibility and acceptable risk. Together, Table 1 and Figure 3 provide a practical methodological basis for investigating how interaction with MASS may affect conventional OOW behaviour in mixed-traffic environments.

6. Conclusions

In this paper, we have explored the complex dynamics between conventional ships and Maritime Autonomous Surface Ships (MASS) from the perspective of Officers of the Watch (OOWs) navigating in mixed-traffic environments. While current MASS research predominantly focuses on the capabilities and behaviour of autonomous ships, the role of the conventional OOW as an active interaction partner remains underexplored. Using the collision-prevention framework as an analytical lens, we argue that the OOW's situational awareness, motion prediction and mental models play an important role in interpreting MASS behaviour, detecting and resolving conflicts, and determining whether, when and how to intervene to ensure safe navigation. Mixed-traffic safety should therefore be considered not only in terms of the performance of the MASS itself, but also in terms of how its behaviour is perceived, understood and anticipated by conventional OOWs.

Several challenges have been identified, including communication with MASS, the application of the COLREGs, operational uncertainty, insufficient knowledge and training regarding MASS, and issues related to the OOW's trust in and the trustworthiness of MASS. These challenges may influence the OOW's collision-avoidance decisions and demonstrate why the conventional ship perspective should be incorporated into MASS development, training and mixed-traffic safety assurance. The practical implications identified in this review should, however, remain evidence-dependent and be further refined as empirical knowledge of OOW–MASS interaction develops.

To address this research gap, this paper proposes using Full Mission Bridge Simulators (FMBS) to investigate mixed-traffic interactions through scenario-driven studies focusing on conventional OOWs. The proposed research questions and experimental approach provide a structured basis for first establishing OOW behaviour during normal mixed-traffic encounters and subsequently extending these studies to more demanding operational conditions. We believe that the proposed experimental approach and research questions can support future simulator-driven research and provide an effective and safe way to investigate how interaction with MASS affects OOW behaviour and the collision-prevention process in increasingly automated maritime operations.

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Abbreviations

The following abbreviations are used in this manuscript:

ACCSEAS	Accessibility for Shipping, Efficiency Advantages and Sustainability
AI	Artificial Intelligence
AIS	Automatic Identification System
COLREGs	Convention on the International Regulations for Preventing Collisions at Sea
CPA	Closest Point of Approach
ECDIS	Electronic Chart Display and Information System
EMSA	European Maritime Safety Agency
FMBS	Full Mission Bridge Simulator(s)
IMO	International Maritime Organization
LOA	Level of Autonomy
MASS	Maritime Autonomous Surface Ship(s)
M/V	Motor Vessel
NASA-TLX	National Aeronautics and Space Administration Task Load Index
OOW	Officer of the Watch
ROC	Remote Operations Centre
RQ	Research Question
SA	Situational Awareness
SAGAT	Situation Awareness Global Assessment Technique
SART	Situation Awareness Rating Technique
SCC	Shore Control Centre
STM	Sea Traffic Management
TCPA	Time to Closest Point of Approach
TEU	Twenty-foot Equivalent Unit
VHF	Very High Frequency
XAI	Explainable Artificial Intelligence

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