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Research paper

Vessel traffic services for maritime autonomous surface ships within the maritime service portfolios framework

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ABSTRACT

Under the International Maritime Organization's (IMO) e-Navigation strategy, standardised digital information exchange between ships and shore-based systems is essential for supporting both human operators and Maritime Autonomous Surface Ships (MASS). However, the existing Vessel Traffic Services (VTS) within the Maritime Service Portfolios (MSPs) remain primarily designed for conventionally manned ships, and their applicability to MASS has not yet been sufficiently addressed in terms of machine interpretability, service delivery timing, and dissemination mode. This study proposes a shore-based MASS-oriented VTS framework at the service and architectural levels. First, a structured MASS-oriented VTS framework is developed within the MSPs by incorporating Autonomous Navigation Systems (ANS) decision requirements, fine-grained service content, and machine-interpretable data formats. Second, a hybrid VTS dissemination mechanism is designed by combining periodic dissemination with event-triggered delivery, as well as broadcast and addressed communication, to support both baseline situational awareness and decision-relevant service provision. Third, a platform-based implementation of the proposed VTS framework is presented through service generation and a case-based instantiation in Yingkou Port, illustrating how the proposed framework can be instantiated in a specific port context. This study provides a service-level framework for bridging conventional shore-based VTS provision and the decision-support requirements of MASS. The proposed framework is potentially compatible with S-100-based data modelling and VDES-based service dissemination, while supporting service information that is both human-readable and parsable by ANS.

1. Introduction

The integration of Maritime Autonomous Surface Ships (MASS) into the International Maritime Organization (IMO) agenda began with a regulatory scoping exercise launched in 2017, in which the Maritime Safety Committee (MSC) assessed the applicability of existing IMO instruments to MASS operations (Alamoush et al., 2024; IMO, 2017). Since then, the IMO has advanced towards a goal-based regulatory framework for MASS, and completed the non-mandatory MASS Code for voluntary implementation in 2025 (IMO, 2025). This Code is intended to serve as the foundation for future mandatory requirements governing the safe operation of MASS.

MASS employ Autonomous Navigation Systems (ANS) that integrate perception, sensor fusion, and intelligent decision-making to support velocity and route optimisation (Munim et al., 2025). For fully MASS, the ANS assumes full responsibility for guidance, navigation, and control, collision avoidance, and regulatory compliance. However, onboard sensing alone is often insufficient in congested or complex waterways, making information exchange with other vessels and shore-based systems essential. This requirement was formally recognised at the MSC 108 meeting in May 2024, where the IMO updated shore-based Maritime Service Portfolios (MSPs) to include MASS-specific provisions (IMO, 2024).

Among the various shore-based Maritime Services within the MSPs, Vessel Traffic Services (VTS) defines the functional requirements for the digital exchange information between ships, maritime regulatory authorities, and shore-based users. VTS are shore-based services implemented to monitor and manage vessel movements within a designated

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service area, thereby enhancing navigational safety, operational efficiency, safety of life at sea, and environmental protection. According to MSC.1/Circ.1610/Rev.1 (IMO, 2024), VTS are positioned as digital information services for the electronic exchange of information and may be delivered through multiple technical means, including Automatic identification System (AIS), VHF Data Exchange System (VDES) messages, IP-based communication, S-100-based product specifications, and other international standards. This indicates that the IMO has already provided a service-level basis for digital VTS information exchange involving conventional ships, MASS, and shore-based users. However, the existing VTS descriptions remain primarily generic and descriptive, and do not yet provide sufficiently fine-grained service elements, explicit machine-interpretable data structures, or clearly defined event-triggered dissemination logic for ANS.

This limitation prevents conventional VTS provision from fully meeting the decision-making requirements of ANS in the following respects: first, the service content is not sufficiently machine-readable to be directly consumed by autonomous systems; second, the timeliness requirements for different types of safety-related information are not explicitly specified; third, the triggering conditions for service dissemination are not clearly formalised as operational events; and fourth, the assurance mechanisms required for service delivery in dynamic port environments remain underdeveloped. These limitations are especially critical in mixed-traffic waters, where MASS must interpret shore-based information together with onboard perception, traffic rules, and interactions with conventional vessels. The specific differences between the conventional VTS framework and the VTS framework required for MASS, in terms of service content, data format, dissemination mode, triggering logic, target users, and ANS compatibility, are presented in Appendix A.

To address the above research gap, this paper proposes a MASS-oriented extension of VTS at the service and architectural levels. In this paper, VTS content does not refer to general information in a broad sense, but to specific information elements provided by shore-based systems to MASS, including traffic situations, environmental conditions, regulatory constraints, and risk events that can be accurately interpreted and effectively used by ANS. The research objective is to reformulate conventional VTS content into deterministic, fine-grained, and machine-interpretable information elements, and to develop an event-triggered hybrid broadcast/addressed dissemination mechanism for delivering such information to MASS in mixed-traffic operations. This dissemination mechanism focuses on under what conditions and in what manner shore-based information should be delivered, with the aim of avoiding excessive redundant information that may increase the computational burden of ANS or even interfere with its decision-making. It should be clarified that MASS-side autonomous navigation algorithms refer to the onboard decision-making and control modules deployed on MASS, including perception fusion, risk assessment, route planning, collision-avoidance decision-making, and motion control. Therefore, this paper focuses on what information should be provided by VTS, when it should be disseminated, and how it should be structured, so as to better support ANS in performing the above functions. However, it does not investigate how a specific MASS should use such information, nor how these functions should be implemented in a particular ANS.

The specific contribution of this study lies in the machine-interpretable reformulation of VTS content and the design of a service dissemination mechanism that is compatible with MASS decision logic. By translating conventional VTS information into structured service elements, the framework enhances the usability of shore-based VTS information for autonomous systems while preserving its interpretability for human operators. Furthermore, the framework is designed to remain neutral with respect to specific ANS architectures, making it potentially applicable to rule-based, learning-based, and hybrid autonomous navigation systems. In practical terms, the proposed framework also highlights the potential compatibility of MASS-oriented VTS with IHO S-100-based data modelling and VDES based service dissemination, which constitutes an important implementation advantage for future digital maritime service infrastructures. Within the IMO e-Navigation and Maritime Service Portfolios (MSPs) framework, the term “MASS-oriented VTS” in this study is not intended to denote an autonomous or unmanned VTS. Rather, it refers to a shore-based service and information-exchange framework designed to enhance the semantic interoperability between human-centred VTS provision and ANS-oriented information consumption. The central problem addressed in this study is that conventional VTS information, although operationally meaningful to human operators and conventional vessels, is not sufficiently structured, deterministic, or machine-interpretable to be directly consumed by MASS. Accordingly, the contribution of this study does not lie in the direct optimisation of MASS manoeuvring behaviour or onboard control performance. Instead, it lies in the reformulation of conventional VTS information into shared service objects that remain human-readable while becoming parsable by ANS, and in the establishment of a structured, machine-interpretable, and event-triggered VTS framework that bridges conventional shore-based VTS provision and the information requirements of ANS in mixed-traffic port environments.

Following this introduction, Section 2 reviews existing literature on shore-based maritime services, with a focus on VTS content and dissemination timing, and identifies gaps that motivate the development of a MASS-oriented VTS dissemination framework. Section 3 proposes a fine-grained VTS content data model based on the decision-making characteristics of ANS and analyses potential events triggering VTS dissemination. Building on this analysis, a hybrid broadcast/addressed dissemination mode is developed and integrated into the proposed VTS dissemination framework. The aim is not to prescribe what goes into the quantification of collision risk or navigational efficiency, but to address a structural limitation in existing VTS by reformulating service content and dissemination mechanisms to make them usable by ANS. The contribution therefore lies in enabling deterministic, machine-interpretable service delivery rather than in evaluating downstream control performance. Section 4 illustrates the applicability and practical relevance of the proposed framework through a case study of Yingkou Port, while Section 5 presents an experimental platform illustrating the proposed VTS content and dissemination mechanisms for MASS. Finally, Section 6 summarises the conclusion of the study.

2. Literature review

2.1. Shore-based VTS content for MASS

Existing studies have demonstrated the feasibility of enhancing situational awareness of vessels through multi-sensor fusion, such as integrating AIS with: Closed-circuit television (CCTV) for stable ship tracking (Chen et al., 2008), combining AIS based motion models with particle filtering for trajectory prediction (Yoo et al., 2018), and fusing AIS, radar, and visual data within VTS for real time vessel monitoring (Chen et al., 2022). Others have leveraged hydrodynamic and meteorological information to enhance VTS by identifying hazardous situations. For example, Zhang et al. (2022) leveraged high precision Global Navigation Satellite Systems (GNSS) to directly measure seabed elevations to provide real time water depth information, while Zhang and Zhang (2021) developed a maritime service oriented pilotage model that integrated tidal forecasts to determine safe transit windows for large vessels in shallow waters. Similarly, Adland et al. (2021) applied deep learning methods to infer meteorological conditions from AIS-derived vessel trajectories and predict weather-related navigational risks.

Although these approaches provide robust target tracking and environmental data analysis within shore-based coverage areas, they are primarily designed for conventional vessels. The resulting outputs are not transformed into standardised, machine interpretable VTS content, nor do they address dissemination timing, delivery mechanisms, or

integration with ANS decision making. Consequently, these approaches do not meet the requirements for delivering actionable VTS to MASS.

Recent studies on MASS navigation further indicate that downstream autonomous navigation technologies require not only enhanced perception, but also structured and decision-relevant service content that can be directly understood by autonomous navigation systems (ANS). In the field of collision avoidance, Huang et al. (2020) proposed a time-varying collision risk measure, while Wang et al. (2020) developed a modified velocity-obstacle-based collision avoidance decision-making system that comprehensively considers ship manoeuvrability, Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) constraints, multi-ship encounters, and the dynamic behaviour of target ships. More recent studies have further incorporated COLREGs into trajectory planning and multi-ship decision-making. For example, Han et al. (2024) embedded COLREGs into the trajectory-searching process through virtual obstacles and spatial-temporal navigation corridors; Song et al. (2024) integrated situation-aware knowledge maps with the Dynamic Window Approach to support rule-compliant local path planning; and Zhang et al. (2025) proposed a collaborative collision avoidance algorithm for complex multi-ship encounter scenarios.

These studies indicate that MASS collision avoidance and trajectory planning increasingly rely on machine-interpretable information. However, most existing onboard decision-making methods still focus primarily on the optimal decision-making of a single own ship. Therefore, it is necessary to adopt a shore-based VTS perspective to provide regionally consistent traffic situation understanding and decision-support service content. This requirement is also evident in recent MASS path planning and decision-support studies. Akdağ et al. (2024) developed a decision-support system for MASS trajectory planning by incorporating factors such as wind, current, tidal information, and narrow-channel conditions. Yun et al. (2024) investigated global path planning in port waters by explicitly modelling navigational constraints such as anchorage areas, traffic lanes, and water depths. Elements such as anchorage boundaries, traffic flow directions, VTS reporting lines, temporary restricted areas, and port traffic organisation rules cannot be reliably obtained by shipborne sensors alone. These elements require standardised shore-based information support and must be expressed in a form that can be used by MASS decision-making systems. Moreover, MASS services should not be limited to machine-to-machine information exchange. Huang et al. (2020) emphasised the importance of human-machine cooperation during collision avoidance and pointed out that future maritime traffic will involve the long-term coexistence of conventional vessels, remotely controlled ships, and MASS. Therefore, VTS content for MASS should also be human-understandable, regulator-observable, and compatible with human supervision.

Although several studies have attempted to extend VTS functions beyond conventional information provision, their focus has mainly remained on traffic management, reporting, or information modelling for human centred operations. Priyatna and Gatinaud (2020) proposed that an intelligent VTS should support advanced functions, including passage plan allocation, mandatory reporting, optimal speed advisories, and collision avoidance optimisation. However, their work does not systematically define service content, data formats, or interfaces, nor does it consider the decision-making requirements of machine intelligence. Similarly, Zhang et al. (2019) introduced an adaptive, scenario based VTS dissemination approach for managing traffic conflicts in congested waterways, but the emphasis remains on traffic management logic rather than the delivery of standardised, machine interpretable services. From a data modelling perspective, Zhang et al. (2020) and Wang et al. (2017) employed the IHO S-100 framework to develop intelligent maritime service and reporting concepts for port areas. While these studies advance the standardisation of maritime information, they remain largely conceptual and lack the technical and operational specificity required for practical VTS implementation, particularly in support of MASS.

Moreover, recent studies on Large Language Model (LLM) enabled navigation decision making and VTS decision support further reinforce this requirement. Navigation-GPT shows that LLM based navigation agents require structured inputs, such as AIS, radar, ENC data, collision risk, and encounter type, to generate COLREGs compliant collision avoidance decisions (Ma et al., 2026). CORALL indicates that risk aware and COLREGs guided decision making depends on explicit risk indicators, encounter classification, and explainable decision outputs (Agyei et al., 2025). VTS-LLM demonstrates the potential of combining structured vessel databases with maritime knowledge to identify risk prone vessels through natural language queries, but it remains mainly oriented toward operator situational awareness rather than standardised VTS for MASS (Sun et al., 2025). In addition, AIS based trajectory prediction and monitoring studies indicate that predictive information, such as expected vessel trajectories and behaviour patterns, is also important for downstream autonomous navigation (Chen et al., 2026; Xie et al., 2025).

However, although Navigation-GPT type frameworks show promise for high level navigation reasoning, their outputs are not inherently standardised for ship shore data exchange and may be affected by hallucinations and non-deterministic responses. Therefore, they should not be used as standalone safety critical decision-making systems for MASS. Instead, a deterministic, machine interpretable, and standard compliant service layer is still required to ensure reliable interfacing with ANS. Existing studies on shore-based traffic services and intelligent maritime information systems, however, have not yet provided a systematic framework for organising such information into standardised, machine interpretable, and regulator observable services.

The above studies clarify the types of VTS information that should be reformulated for MASS, including traffic states, environmental constraints, collision risks, and related information. However, for ANS, the value of such services depends not only on whether the information is machine interpretable, but also on whether it is delivered at an appropriate time. If the information is disseminated too early, too late, or without relevance to the current navigational context, even well structured content may lose its decision value. Therefore, after examining VTS service content, it is necessary to further discuss how dissemination timing should be adapted to MASS operational requirements.

2.2. *Shore-based VTS dissemination timing for MASS*

In VTS service areas, information dissemination has traditionally relied on periodic broadcasts, predefined schedules, or vessel requests. These mechanisms are still necessary for maintaining baseline situational awareness, but their suitability for MASS depends on whether they can be complemented by event triggered delivery in decision relevant situations. Existing dissemination schedules vary widely across VTS areas, and therefore historical ship behaviour has been analysed to inform broadcast timing. Scully et al. (2020) used AIS data to extract traffic composition, spatial distribution, voyage frequency, and seasonal patterns to support Traffic Organisation Services scheduling. Guo et al. (2022) analysed the port entry and exit processes for MASS by dividing them into five operational stages: crossing the VTS reporting line, anchorage waiting, channel transit for port entry, berthing operations, and channel departure. Then an event triggered service dissemination mechanism aligned with these stages is proposed. From a broader autonomous navigation perspective, Hinostroza and Lekkas (2024) developed a temporal mission planning framework for MASS, in which high level tasks, such as moving to a specific location, switching operational modes, docking, and cargo handling, are organised as a temporal sequence and integrated with guidance, navigation, and control systems. Wang et al. (2023) further proposed a maritime autonomous navigation decision making system. While effective at capturing macroscopic spatio-temporal and operational patterns, these approaches do not address finer grained timing requirements or vessel specific dynamics.

At a more granular level, several studies have examined individual

vessel interactions to inform service dissemination timing. Porathe and Rødseth (2019) suggested extending VTS authority to enhance MASS situational awareness and proposed providing clear route adjustment recommendations at varying time intervals. Altan and Otay (2018) applied data mining techniques to historical AIS data to develop probabilistic models for predicting ship encounters in narrow waterways, enabling the estimation of accident probabilities that can inform VTS service scheduling. In relation to collision risk reasoning, Huang and van Gelder (2020) emphasised that collision risk assessment should be connected with conflict resolution capability and proposed a time varying collision risk measure to trigger evasive actions before the conflict becomes unavoidable. From the perspective of COLREGs compliant collision avoidance, Wang et al. (2020) developed a modified velocity obstacle based collision avoidance decision making system that continuously updates decisions according to multi ship encounters, ship manoeuvrability, COLREGs constraints, and target ship behaviour. Ali et al. (2024) proposed a safety enhanced path planning method that combines global path planning with local dynamic obstacle avoidance. In addition, Choi et al. (2025) developed a Monte Carlo simulation method for evaluating collision avoidance algorithms in port congestion zones by constructing typical encounter scenarios and randomly generating obstacle positions, speeds, and headings. These studies indicate that VTS dissemination timing should be sensitive not only to scheduled reporting points or service areas, but also to collision risk evolution, encounter probability, manoeuvring margin, and scenario specific illustration results.

Beyond collision centric interactions, Wang et al. (2023) characterised manoeuvring centric ship behaviours in port areas, including merging, diverging, crossing, and turning manoeuvres. Building on this, Chen et al. (2022) formalised ship behaviour knowledge using semantic networks and transformed these into dynamic Bayesian neural networks trained on large scale traffic data, enabling reasoning under uncertainty and revealing behaviour patterns relevant to when services should be disseminated. These studies suggest that VTS dissemination timing should not be determined only by geometric proximity or fixed reporting points. It should also consider behaviour transitions, manoeuvring intentions, and the evolution of traffic interaction patterns, especially in mixed traffic environments involving conventional ships and MASS.

Recent studies on LLM-based mission planning, trajectory prediction, autonomous navigation, and system verification further support the necessity of combining periodic dissemination with event-triggered delivery in VTS for MASS. Christensen et al. (2025) showed that MASS should be capable of replanning missions in response to human commands and unforeseen situations. Jiao et al. (2026) indicated that ship trajectories and encounter risks can be predicted by integrating multi-ship interaction topology, hierarchical temporal modelling, geospatial semantics, and uncertainty estimation. Kim and Yoo (2025) showed that structured vision-language reasoning can support risk assessment and navigation decision-making, implying that semantic scene changes, such as hazardous objects, restricted boundaries, or complex navigational contexts, may also serve as service-triggering events. Li et al. (2026) reviewed the application of LLMs in autonomous intelligent system testing, including test scenario generation and real-time monitoring, which further supports the need to incorporate scenario-based illustration results into event-triggered dissemination logic.

These studies indicate that VTS dissemination timing for MASS should be determined not only by fixed schedules or vessel requests, but also by the dynamic evolution of missions, traffic conditions, environmental factors, and navigational risks. However, existing research mainly focuses on onboard planning, trajectory prediction, risk reasoning, or system verification, without directly addressing shore-based VTS dissemination or the ANS requirements for interpretable content, deterministic triggering, and timely communication. Therefore, a MASS-oriented shore-based VTS dissemination mechanism is needed to integrate periodic broadcast, event triggering, prediction-aware delivery, and addressed transmission into a structured, timely, and operationally actionable VTS service framework.

Based on the above limitations of shore based VTS, a systematic MASS oriented service dissemination framework to address the temporal mismatch between existing information delivery practices and MASS operational requirements is proposed. The framework retains periodic dissemination to maintain baseline situational awareness, while introducing event triggered logic. By integrating machine interpretable VTS content with a hybrid broadcast and addressed service dissemination strategy, the proposed framework enables timely, relevant, and decision supportive information delivery for ANS. The main contributions are as follows:

Based on the above limitations of shore based VTS, a systematic MASS oriented service dissemination framework is proposed. Aiming to address the temporal mismatch between existing information delivery practices and MASS operational requirements. The framework retains periodic dissemination to maintain baseline situational awareness. It also introduces event triggered logic to support timely service delivery in decision relevant situations. By combining machine interpretable VTS content with a hybrid broadcast and addressed dissemination strategy, the proposed framework provides timely, relevant, and decision supportive information for ANS. The main contributions are as follows:

- A structured MASS oriented VTS framework within the Maritime Service Portfolio structure, incorporating ANS decision requirements, fine grained service content, and machine interpretable data formats.
- A hybrid VTS dissemination mechanism that combines periodic dissemination with event triggered delivery, as well as broadcast and addressed communication, to support both baseline situational awareness and decision relevant service provision.
- A platform-based implementation of the proposed VTS framework for MASS, instantiated through service generation and a case study in Yingkou Port to demonstrate its applicability in a real port context.

3. VTS content aligned with MASS decision logic

3.1. Universal VTS content design for MASS

Shored based VTS content for MASS is designed under a decision-oriented semantic information modelling framework, ensuring that the service information is simultaneously human-interpretable and machine-consumable. Shore-based VTS content for MASS is designed under a decision-oriented semantic information modelling framework. The core contribution of this section is to reconstruct VTS content from human-oriented descriptive information into machine-interpretable service objects that can be parsed, instantiated, and invoked by Autonomous Navigation Systems (ANS). Consistent with the operational paradigm articulated in the IMO MASS Code (IMO, 2025), the ANS of MASS is generally expected to achieve situational awareness through onboard sensing and data fusion, execute collision-avoidance actions in accordance with the COLREGs, and perform route execution and voyage monitoring. Accordingly, shore-based VTS should not replace onboard autonomy, but should complement it by providing decision-critical information that is unavailable onboard, inherently uncertain, or operationally authoritative from shore. Such information may serve either as raw input data for ANS autonomous decision-making or, when necessary, as transparent decision supplements for supervisory recommendation.

Furthermore, machine-interpretable service content for MASS should not only specify what information is provided, but also clarify under which operational boundaries and risk states such information can be recognised, invoked, and interpreted by the ANS. The “operational context” perspective emphasised in the MASS Code, VTS information should support ANS operation within clearly defined operational boundaries, thereby contributing to navigational safety within the

Operational Design Domain (ODD). The MASS Code establishes a conceptual relationship among the Operational Envelope (OE), ODD, degraded states, fallback states, and contingency plans. However, it has not yet provided a harmonised operational specification for severity grading, triggering thresholds, or the mapping between degraded and fallback states. Therefore, the definition of OE/ODD boundaries remains dependent on the implementation strategies of Administrations and operators, and is expected to be iteratively refined during the experience-building phase.

In this respect, the shore-based VTS framework proposed in this paper remains neutral regarding the specific parametrisation of OE/ODD, as illustrated in Fig. 1. Regardless of whether future regulatory consensus adopts stricter or more permissive OE/ODD settings, the proposed VTS content can be instantiated as a consistent machine-interpretable information layer. Within the applicable ODD, it provides structured input data to support ANS decision-making. When operating conditions approach or exceed defined boundaries, it provides transparent decision supplements to support graded escalation and, where necessary, takeover or directive control. Thus, the framework does not presuppose a specific severity taxonomy for degraded or fallback states, while remaining compatible with different OE/ODD governance and implementation regimes.

Building on the above logic, this paper reconstructs VTS content into a universal machine-interpretable model using UML modelling, in accordance with the S-100 data specification, and organises it around three primary semantic service objects: (i) ship motion state and intent information service, which describes a vessel's position, identity, motion state, and intended behaviour; (ii) operational navigation environment information service, which characterises waterways, hydro-meteorological conditions, recommended routes, traffic separation schemes, and aids to navigation; and (iii) other safety information relevant to operations within the VTS area. These information elements are intended to enhance situational awareness and traffic coordination rather than directly prescribe manoeuvring actions. Compared with conventional manned navigation, where service effectiveness mainly depends on human understanding and judgement, MASS requires these elements to be encoded with explicit attributes, constraints, and relationships that are accessible to ANS.

To support this reconstruction, the proposed VTS service framework adopts the S-100 Universal Hydrographic Data Model as the basis for service data specification, consistent with current e-Navigation practices. On this basis, the detailed content, format, and instantiation process of each VTS information item are further formalised in Appendix B.

3.2. *Event-triggered hybrid dissemination mechanism of VTS to MASS*

The mechanism adopts the VHF Data Exchange System (VDES) as the communication medium. Although VDES has not yet been universally mandated as a carriage requirement for international shipping, it has been widely recognised as an enabling technology for maritime digital communication and MASS-related services. VDES integrates the core safety broadcasting function of AIS, the structured maritime service exchange enabled by application-specific messages (ASM), and the higher-capacity data transmission provided by terrestrial and satellite VDE links, thereby supporting both broadcast and addressed communications. Accordingly, the proposed framework does not prescribe fixed upper bounds on latency or update rates, as these are constrained by local communication infrastructure, service requirements, and regulatory arrangements. Instead, without introducing additional strong assumptions and while remaining compatible with existing international standards and installed shipboard navigation and communication capabilities, the framework establishes an event-triggered hybrid dissemination logic that enables VTS service delivery through minimal incremental modification, avoiding unnecessary changes to onboard systems.

As illustrated in Fig. 2, the proposed mechanism is built under the VDES service paradigm, in which periodic broadcast and addressed dissemination are supported by design. However, in conventional practice, the timing of dissemination is often determined heuristically. To improve verifiability and implementability while preserving the existing architecture, this study retains the baseline modes of periodic broadcasting and addressed interaction, and further introduces region context discretisation as the triggering foundation. This module structures continuous navigational contexts into a set of identifiable discrete events, such that both dissemination modes can be explicitly activated by events.

Specifically, the blue path represents broadcast services. Pseudo-target information, hydro-meteorological information, and

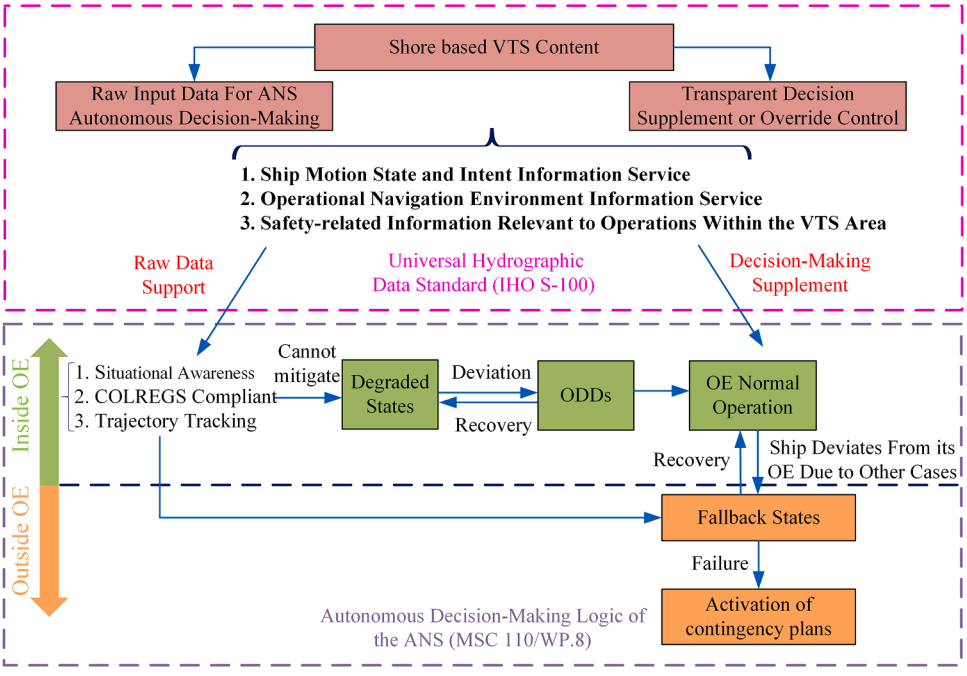


Fig. 1. Machine-interpretable reconstruction of shore-based VTS content oriented to MASS decision logic.

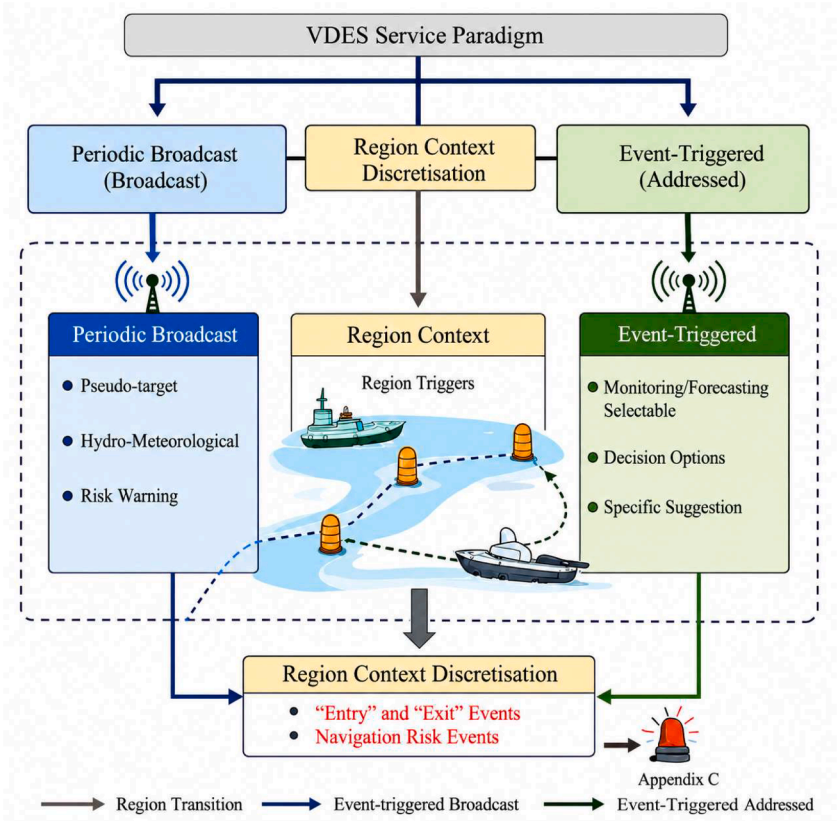


Fig. 2. Design of shore based broadcast/addressed VTS triggering events.

navigational risk-warning information are treated as region-shared contextual information and disseminated via periodic broadcast to traffic participants within the region. The green path represents addressed services. Shore-based outputs delivered on demand to a target vessel are progressively strengthened with increasing risk level and shore-side intervention intensity, covering monitoring or forecasting services, suggestion options, and specific suggestions. Activation of both service types is driven by the event set generated through region context discretisation, primarily including vessel "entry/exit" events across regional units and navigation risk events capturing risk evolution. The corresponding trigger criteria and message-level details are provided in Appendix C to support reproducibility and practical deployment.

3.3. *Platform-level workflow of VTS dissemination*

Fig. 3 presents the platform-level workflow of the proposed hybrid VTS dissemination mechanism. The shore-based VTS provider acquires multi-source data, including AIS reports, shore-based observations, hydro-meteorological data, and relevant navigation and traffic-management rules. After time alignment, source tagging, region matching, and vessel–region association, the data are mapped to pre-defined regional context units. The system then identifies region-level events arising from changes in shared regional context and vessel-level events arising from changes in vessel-specific risk, state, or operational requirements. This process supports VTS providers in situation observation, event recognition, and service decision-making rather than fully autonomous service provision.

Detected events are mapped to corresponding service content and dissemination modes. Region-level events are generally disseminated through broadcast, whereas vessel-level events are primarily disseminated through addressed communication. The final mode may be adjusted according to the affected scope, event severity, and local procedures. Each VTS object is instantiated according to the S-100-based service model and contains essential fields such as the service ID, event ID, region ID or target vessel ID, timestamp, validity period, and dissemination mode. Appendix D summarises the relationships among service categories, message types, triggering situations, dissemination modes, and intended receivers.

The generated information is disseminated through VDES-compatible communication means. The platform continuously monitors the event status and updates, cancels, or re-triggers messages when necessary. The workflow focuses on VTS information generation and service orchestration; VDES channel optimisation, bandwidth allocation, encryption, authentication, and equipment-specific interfaces remain subject to local deployment conditions and regulatory requirements.

4. Case-based instantiation of the event-triggered VTS dissemination framework

Based on the above theoretical framework, a universal VTS content model has been established, and the proposed services have been summarised in terms of service categories, representative message types, triggering conditions, dissemination modes, and intended receivers. To further clarify the applicability of this framework, this section presents a case-based modelling process for instantiating the proposed theory in a specific port water area. Appendix E further specifies the correspondence between the universal service model and the service instances generated for the selected water area. By instantiating the proposed framework in the Yingkou Port environment, the VTS content are further refined and supplemented, thereby forming a more concrete operational framework.

Fig. 4 shows the Yingkou Port study area, which is partitioned into ten functionally distinct water areas and annotated with recommended inbound/outbound routes and channel centrelines. This zoning reflects dominant traffic-flow characteristics and recurring conflict patterns, and

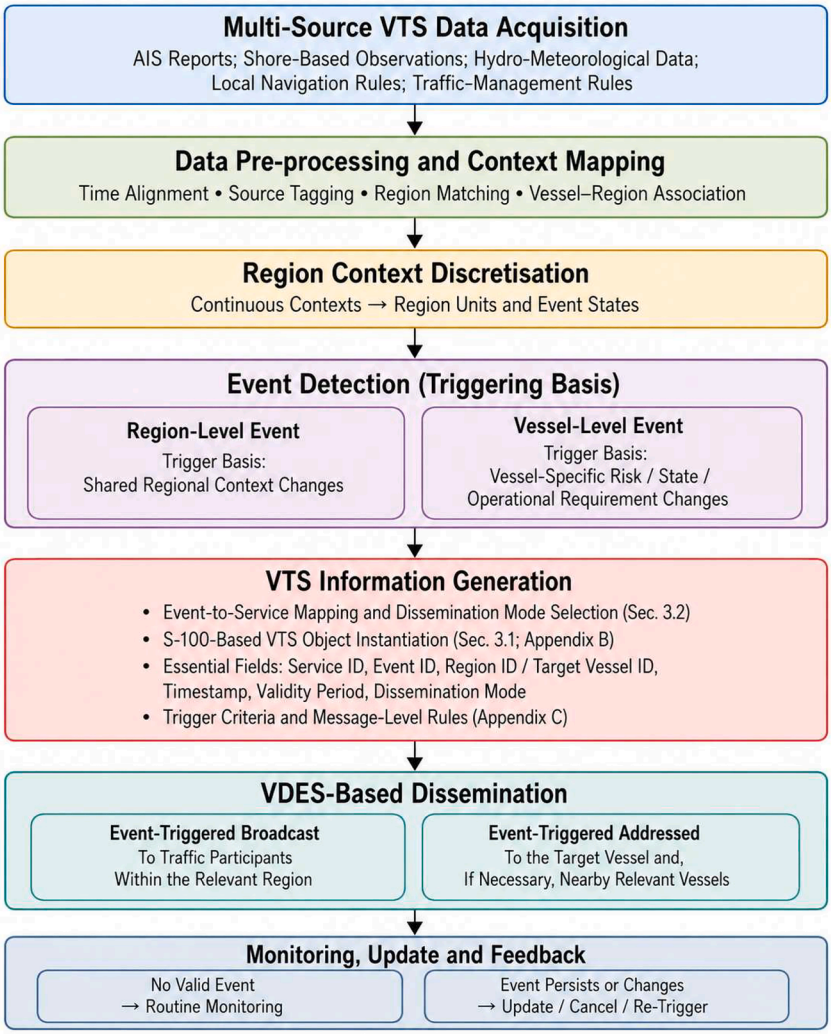


Fig. 3. Platform-level workflow for event-triggered hybrid VTS dissemination.

is used to define operationally meaningful boundaries for shore-side VTS provision. Within each area, vessel behaviour is assumed to be primarily governed by local constraints and to exert limited influence on adjacent areas so broadcast can be area specific or through the entire remit of the VTS coverage area.

Hydro-meteorological influences in the port's waterway are generally limited during non-icy seasons, therefore, wind, waves, and currents typically have minor impact on manoeuvrability, and the tidal regime is predominantly semidiurnal. By contrast, during the icy seasons, navigational risk can increase markedly requiring further safety and time-critical constraints which the VTS can be broadcasted through the risk warning class in the proposed framework.

Areas 6, 7, 9 and 10 of Fig. 4, where bi-directional traffic occurs, local port rules stipulate that vessels are subject to explicit separation requirements, whereas navigation outside these areas is primarily governed by "not to impede" obligations that impose weaker and more situational constraints. However, when a developing encounter presents a collision risk, the COLREGs "stand on" and "give way" hierarchy takes precedence and overrides all other provisions.

During the initial deployment of MASS, when autonomous navigation technologies remain under illustration, port authorities typically adopt a conservative operational strategy, restricting operations to designated areas, port basins, or time windows. From a shore based VTS perspective, this controlled environment supports the assumption that irregular or non compliant behaviours common in conventional navigation are unlikely during MASS operations and, if they occur, can be addressed through remote operator intervention. This assumption is particularly appropriate for Yingkou Port, where local rules are straightforward and traffic flows are predominantly unidirectional.

Under these orderly conditions, strict regulatory compliance by MASS is expected to substantially reduce collision risk and limit the escalation of adverse events. Accordingly, shore based VTS should prioritise targeted supervision, with addressed services and regulatory oversight applied to potential collision risks outside areas 6, 7, 9, and 10. Within the designated channels, inter vessel separation should be monitored, and the safety of MASS port entry and exit, particularly via Area 9, should be actively supervised for high-risk events.

4.1. *Port approach control*

Four representative channel merging/egressing patterns were identified from the local navigation rules and observed traffic flows (Fig. 5). Patterns 1 and 2 occur in close proximity to the breakwater entrance and therefore leave limited time and space for contingency handling by MASS (e.g., re-planning, speed correction, or remote intervention). These patterns are consequently excluded from the supervision scope. By contrast, Patterns 3 and 4 allow the vessel to align its heading with the nominal channel traffic direction prior to merging/egressing and initiate the manoeuvre farther from the breakwater and they are therefore adopted as the nominal supervised behaviours for MASS under

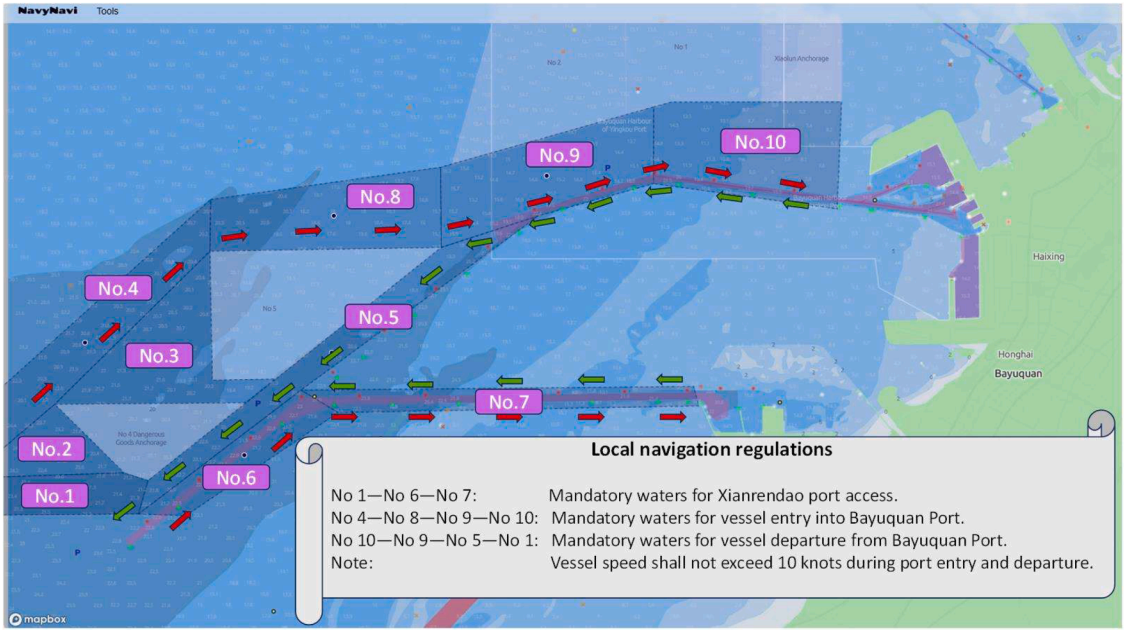


Fig. 4. Division of water areas in Yingkou Port based on traffic flow characteristics and conflict patterns. Based on the survey results, the purple channels indicate unidirectional navigation lanes, the red lines represent recommended inbound routes, and the green lines denote recommended outbound routes.

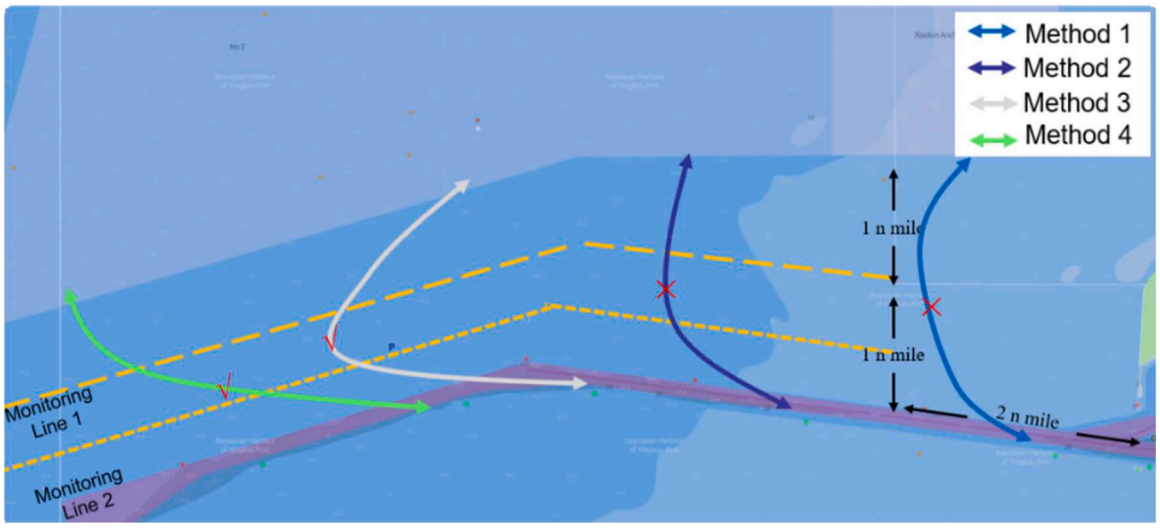


Fig. 5. Four patterns of merging or exiting channels in Yingkou Port.

the proposed *Port Approach Control* service To operationalise supervision and enable deterministic event triggering, two monitoring lines are defined along the approach/egress geometry, as shown in Fig. 5.

The theory proposed in Chapter 3 is applied in Yingkou Port by placing two monitoring lines relative to the channel direction shown in Fig. 5. Under the Yingkou Port management regulations, a vessel that intends to enter the channel is required to keep a minimum safe distance from the nearest vessel ahead and the nearest vessel astern (see Table 1 for the local separation criteria used in this study). If the approaching vessel does not satisfy these spacing requirements, or if it cannot align its heading with the channel traffic direction before entering, the system triggers an addressed VTS intervention. Typical interventions will include instructing the vessel to hold position outside the breakwater, to reapply for entry clearance, or to submit an alternative entry or exit plan.

Table 1
Yingkou Port separation thresholds for vessel space control.

Clearance	Imminent	Urgent	Potential	Safe
Forward	R_a=1.5 n mile	R_b=1.5 n mile	R_c=2.5n mile	$>R_c$
Rear	R_d=0.5 n mile	R_e=1.0 n mile	R_f= 2.0 n mile	$>R_f$

The port-approach service supervises merging or egressing manoeuvres using two monitoring lines aligned with the local channel geometry. monitoring line 1 evaluates whether the planned merge trajectory preserves sufficient spacing relative to vessels already navigating in the channel, while monitoring line 2 verifies that the MASS aligns with the nominal traffic direction before entering or exiting the channel.

Monitoring line 1. - *waypoint-based merge feasibility:* Vessels already in the channel are assumed to follow predefined waypoint sequences released in advance as part of the pseudo-target service. Their short-horizon trajectories can therefore be propagated using AIS speed over ground (SOG) data. At monitoring line 1, the feasibility of the planned

merge is determined by the predicted gaps to the nearest vessel ahead and astern at the merge time.

Let t_0 denote the time at which the MASS reaches monitoring line 1 at coordinates $P_0 = (x_0, y_0)$. Given the planned merging trajectory $M = (P_0, P_1, ..., P_n)$ the merge time is the cumulative travel time to the channel centreline at the commanded speed:

$$t_M = \sum_{n=0}^{N-1} \Delta t_n = \sum_{n=0}^{N-1} \frac{d_{\text{haversine}}(P_{n+1}, P_n)}{v_n} \tag{6}$$

Where $d_{\text{haversine}}(.)$ denotes the Haversine distance between two geographic coordinates and v_n is the SOG along segment n.

Under the waypoint-following assumption, the predicted positions of the nearest vessel ahead (f) and behind (b) along the channel centreline at t_M are obtained via route-constrained propagation. The separation distances relative to the MASS are

$$\begin{aligned} d_{Mf}(t_M) &= d_{\text{haversine}}\left(P_M(t_M), P_f(t_M)\right) \\ d_{Mb}(t_M) &= d_{\text{haversine}}\left(P_M(t_M), P_b(t_M)\right) \end{aligned} \tag{7}$$

A minimum spacing threshold $d_{\min}$ is imposed by the local authority. The merge is declared feasible only if

$$d_{Mf}(t_M) \geq d_{\min} \text{and} d_{Mb}(t_M) \geq d_{\min} \tag{8}$$

Monitoring line 2. - *Manoeuvrability assessment.* If the spacing constraints at monitoring line 1 are satisfied, the vessel continues to monitoring line 2, where its ability to align with the channel traffic flow is assessed, as illustrated in Fig. 6.

Let ψ_M denote the vessel heading at monitoring line 2, and let ψ_C denote the nominal channel traffic direction. The heading misalignment angle is

$$\Delta\psi = |\psi_M - \psi_C| \tag{9}$$

A maximum allowable deviation $\Delta\psi_{\max}$ is specified according to the monitoring-line geometry and channel width to ensure that MASS can merge without excessive rudder activity. The manoeuvrability requirement is therefore

$$\Delta\psi \leq \Delta\psi_{\max} \tag{10}$$

If either monitoring line 1 or monitoring line 2 checks fail, the merge/egress attempt is rejected and an addressed VTS is issued to hold position, re-plan, or otherwise mitigate the risk according to the collision-risk level in Table 1.

4.2. Vessel space control

After a MASS merges into the channel, spacing relative to neighbouring traffic is supervised continuously. Since AIS reports the antenna position rather than the hull, AIS static dimensions (bow, stern, port, and starboard offsets) are used to construct hull-to-hull clearances, forming the safety envelopes illustrated in Fig. 7.

Spacing is partitioned into discrete regimes. Distances greater than the managed upper bounds $[R_c, R_f]$ are safe and require no intervention. Distances within managed envelopes $[R_b, R_c]$ and $[R_e, R_f]$ correspond to potential or urgent danger; in these cases, the VTS issues addressed services directing moderate speed or trajectory adjustments. Breaches of the critical limits R_a or R_d indicate imminent danger and trigger decisive interventions, including remote control of adjacent vessels, to re-establish safe separation. These thresholds are also mainly defined based on the practical traffic-management experience of VTS operators.

Vessel space control in Yingkou Port is applied primarily within areas 6, 7, 9, and 10 (Fig. 4), where bidirectional traffic and port regulations impose explicit separation constraints. Following the hull-to-hull clearance concept in Fig. 7, the VTS continuously computes forward and aft clearances using AIS static dimensions and uses these values to classify separation into the four collision-risk stages. Given the concentration of conflicted traffic in the port-entry corridor (area 9), addressed advisories are prioritised for vessels transiting this area whenever clearances degrade toward the urgent or imminent regimes. Table 1 summarises the calibrated clearance thresholds adopted for Yingkou Port.

4.3. Collision risk assessment

The collision risk of MASS is quantified using the Collision Risk Index (CRI) proposed by Wang et al. (2023). In the proposed framework, addressed VTS are *event-triggered* based on when the real-time CRI score of a monitored vessel crosses predefined thresholds, the shore-based system transitions from routine monitoring to advisory or intervention and issues an necessary action accordingly.

Based on the CRI risk-level intervals, four semantic trigger events are defined—*safe situation, potential danger, urgent situation*, and *imminent danger* —as summarised in Table 2. Considering that the traffic flow directions in Yingkou Port waters are relatively clear, navigational risks mainly arise from inter-vessel interactions and spacing constraints during port entry and departure, rather than from strong coupling between hydro-meteorological conditions and vessel motion. Therefore, no additional risk weighting is assigned to hydro-meteorological

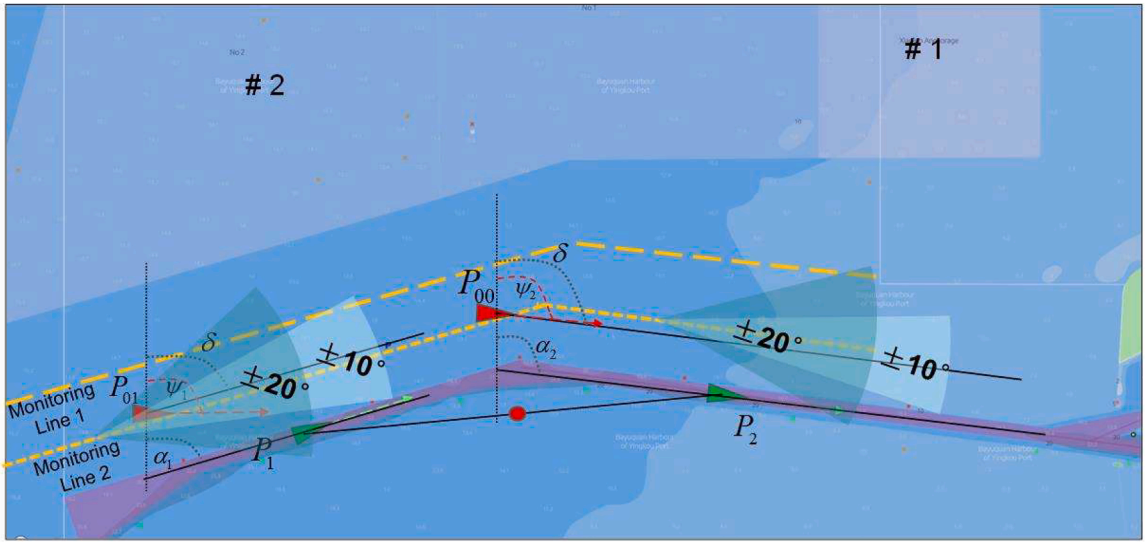


Fig. 6. Model for assessing the manoeuvrability of MASS at monitoring line 2.

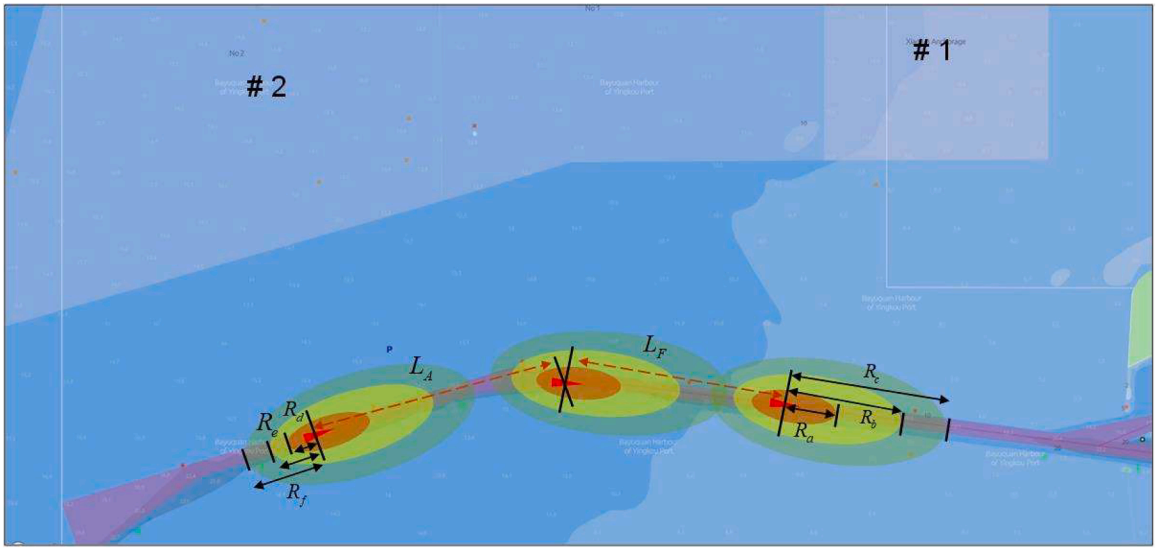


Fig. 7. Vessel space control and separation monitoring for ships navigating in the channel.

Table 2
Addressed VTS triggering events based on collision risk levels.

Stage	Event	Risk level interval	Action
1	Safe	[0.0, 0.4]	Shore-based monitoring
2	Potential	(0.4, 0.6]	Shore-based monitoring
3	Urgent	(0.6, 0.7]	Shore-based advisory
4	Imminent	(0.7, 1.0]	Shore-based decision-making

conditions in this study. Instead, based on the open-water CRI model, the risk-level thresholds are locally calibrated by considering the traffic characteristics of Yingkou Port and the practical experience of VTS operators.

Under normal operating conditions, the MASS navigation decision-making subsystem is assumed to account for manoeuvring capabilities, COLREGs, and local navigation rules. On this basis, shore-based systems can assess whether a vessel adheres to its declared route, sailing parameters, and risk-avoidance strategy, and detect inconsistencies or ambiguity in navigational intent, thereby quantifying collision risk into one of the levels in Table 2. As collision risk increases, this study posits that shore-based systems progressively transition from a monitoring role to an advisory role such that they provide area or vector based recommendations. In the highest risk scenarios, it will assume a decision-making roles that will provides clear alternative manoeuvring sequence.

4.4. Collision avoidance control

Although the COLREGs define collision-avoidance responsibilities, they do not prescribe quantitative thresholds for manoeuvring actions. In practice, the principle of good seamanship requires collision-avoidance manoeuvres to be clearly observable to other mariners. For example, when altering course to avoid collision, human operators typically make a sufficiently large course alteration so that the manoeuvre is evident both visually and on radar. ANS, by contrast, can detect and respond to very small changes, on the order of 1°, which may not be perceptible to human operators. As a result, algorithmic collision-avoidance behaviour may consist of frequent incremental adjustments rather than a single pronounced manoeuvre. Accordingly, this study adopts quantitative indicators that characterise the frequency and consistency of changes in speed, heading, and trajectory, and uses these indicators as event triggers for supervising collision-avoidance behaviour.

(1) Magnitude of speed and heading variations:

Short-term fluctuations in speed and heading are common during normal vessel operation so to distinguish these benign variations from purposeful but non-decisive manoeuvring behaviour, speed and heading variability are examined over a short observation window T_1 of 1 min. Let ψ_t and v_t denote the vessel heading and speed at time t. The standard deviations of heading and speed over T_1 denote by σ_ψ and σ_y are used as indicators of manoeuvring magnitude. Variations below 5° in heading or 0.5 kn in speed are considered steady-state disturbances, whereas moderate fluctuations in the ranges 5° to 10° and 0.5 to 1 kn indicate frequent but limited corrective actions. The magnitude-based manoeuvre event is therefore defined as:

$$E_m = \begin{cases} \text{True}, & (5^\circ < \sigma_\psi < 10^\circ) \vee (0.5\text{kn} < \sigma_\psi < 1\text{kn}) \\ \text{False}, & \text{Otherwise} \end{cases} \tag{1}$$

(2) Incremental changes in track direction:

In addition to instantaneous heading changes, the evolution of the vessel's actual track provides important insight into navigational intent. Using per-minute position samples within T_1, the longitudinal and lateral displacements, $d_{x,k}$ and $d_{y,k}$ are used to compute the course over ground (COG) and its incremental change:

$$Cog_k = \arctan\left(\frac{d_{y,k}}{d_{x,k}}\right), \Delta Cog_k = Cog_k - Cog_{k-1} \tag{2}$$

Small track deflections between 5° and 10° are interpreted as minor course adjustments that do not substantially alter the vessel's trajectory and are therefore insufficient, on their own, to represent decisive collision-avoidance manoeuvres. Such behaviour is captured by the following event definition:

$$E_s = \begin{cases} \text{True}, & (5^\circ \le \Delta Cog_k \le 10^\circ) \wedge (t_k \in T_1) \\ \text{False}, & \text{Otherwise} \end{cases} \tag{3}$$

(3) Frequency of manoeuvring actions:

While isolated small adjustments may be acceptable, repeated large changes over a short period often indicate unstable control, indecision, or ineffective collision-avoidance behaviour. To capture such patterns, manoeuvring frequency is evaluated over a longer time window T_2 of 5 min.

Thresholds are defined for significant changes in heading, speed, and track direction:

$$\Delta\psi_{thre} = 15^{\circ}, \Delta v_{thre} = 15\%, \mathrm{Cog}_{thre} = 15^{\circ}$$

A frequent manoeuvre event is triggered when these thresholds are exceeded multiple times within T_2 reflecting sustained corrective or oscillatory behaviour rather than a single deliberate action. Formally, this is expressed as:

$$E_a = \begin{cases} \text{True} & if\left(\sum_{t\in\Delta T_2} \| ((\Delta\psi_t > \Delta\psi_{thre}) > 3\right) \vee ((\Delta v_t > \Delta v_{thre}) > 3) \\ & \vee((\Delta Cog_k > Cog_{thre}) > 4) \\ \text{False} & Otherwise \end{cases} \tag{4}$$

A vessel is classified as exhibiting frequent manoeuvring behaviour if any of the above conditions is satisfied. The overall event is therefore defined as:

$$E_f = \begin{cases} \text{True} & if(E_s \vee E_m \vee E_a) \\ \text{False} & Otherwise \end{cases}. \tag{5}$$

Whenever E_f becomes true in the supervision area, the shore-based system issues addressed services to the relevant vessel and nearby traffic.

It should be noted that the thresholds in this part are primarily defined with reference to the requirements of "good seamanship" under the COLREGs, particularly the need for collision-avoidance manoeuvres to be clear and readily recognisable. If changes in a vessel's motion state are too small in magnitude or occur too frequently, its collision-avoidance intention may become difficult to recognise, thereby increasing the uncertainty for other vessels in interpreting the encounter situation and manoeuvring intent.

5. Illustration of the instantiated VTS results at Yingkou Port

An VTS information dissemination platform for MASS was developed

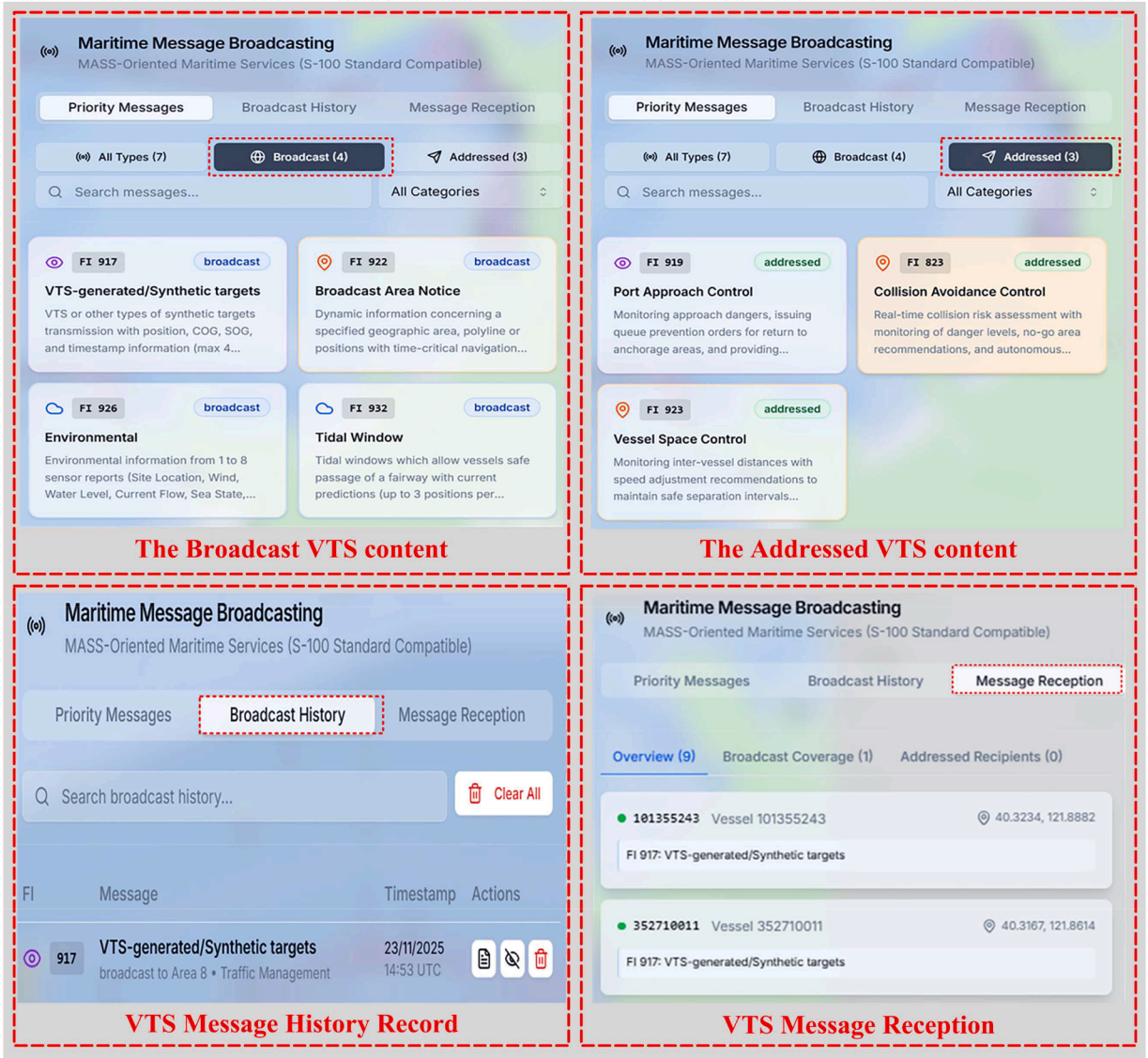


Fig. 8. User interface of the VTS maritime message dissemination platform. (1) Broadcast VTS content, displaying system-wide maritime safety and navigation messages disseminated to all vessels; (2) Addressed VTS content, presenting vessel-specific safety and control messages; (3) VTS message history record, providing a chronological log of previously broadcast messages; and (4) VTS message reception interface, showing real-time reception status and delivery confirmation for individual vessels.

and implemented following on-site investigations at Yingkou Port, drawing on the design framework presented in Section 3 and the instantiation and calibration described in Section 4. The platform uses real-time AIS data from Yingkou Port as practical traffic input for illustrating the platform-level instantiation of the proposed framework under real port traffic conditions. Fig. 8 shows the interface for VTS platform in Yingkou Port compatible with IHO S-100 standard.

Fig. 8 illustrates how the proposed broadcast VTS service logic is instantiated on the platform through service-object editing, event-triggered dissemination configuration, and shore-based display. The upper panel presents four types of broadcast VTS service objects, including pseudo-target, area-notice, environmental, and tidal-window information, showing how region-shared navigational information is organised into structured service objects. The lower panel presents the dissemination configuration process, in which VTS messages are generated based on MASS Entry/Exit events, assigned corresponding priority levels, and formatted according to the S-100-compatible service-object structure defined in the proposed framework. The shore-based display further illustrates how the generated pseudo-target VTS messages are visualised on the platform.

The data used in this instantiation are mainly AIS data, derived from vessel dynamic information collected and analysed in real time by the research team during on-site watchkeeping with the vessel traffic management department from September to November 2024. The corresponding historical trajectories can also be replayed and reviewed through the Navi.Navy platform. Given the real-time nature of data

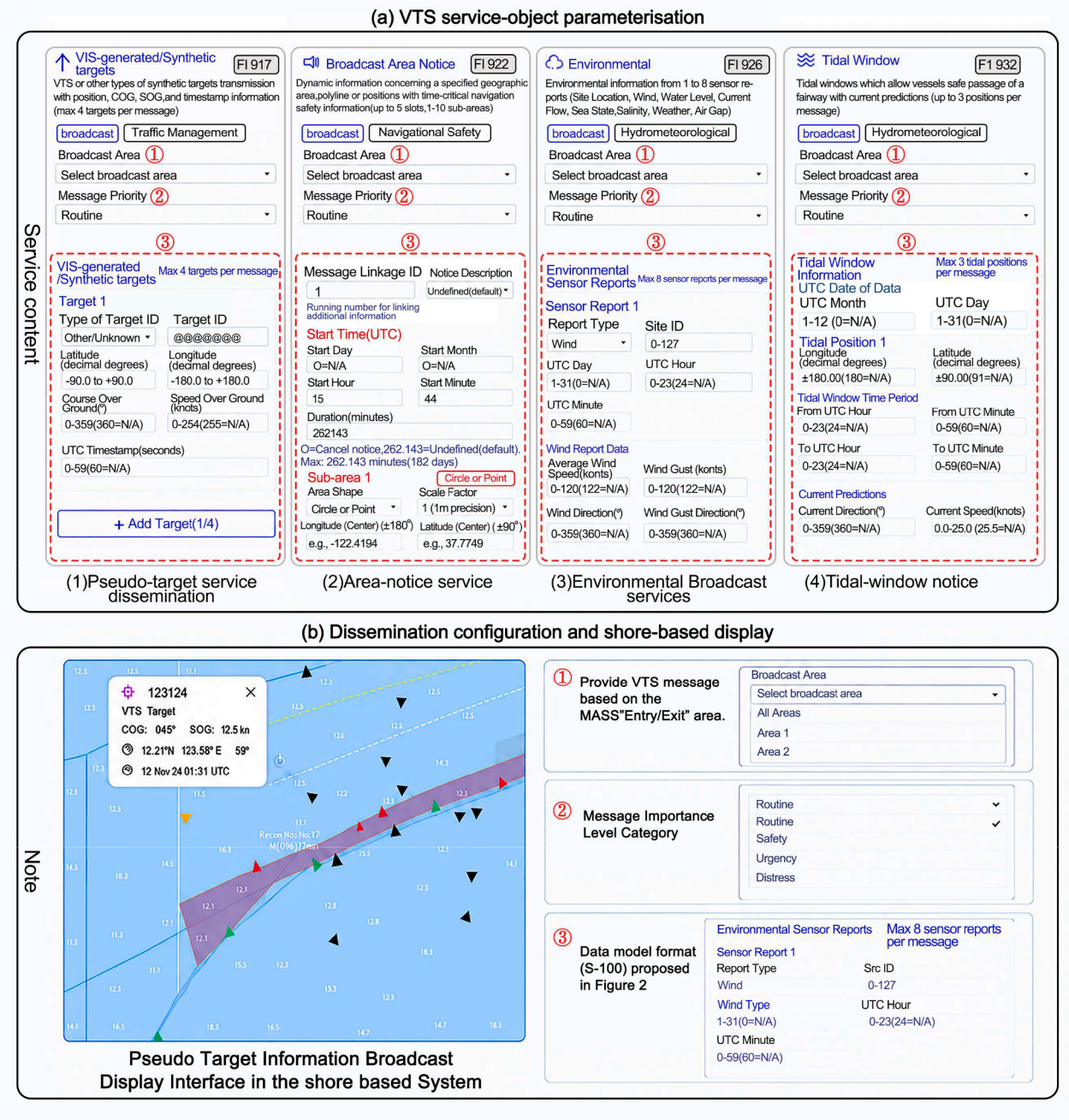


Fig. 9. Platform-based instantiation of broadcast VTS service-object parameterisation and dissemination configuration in Yingkou Port. (a) VTS service-object parameterisation, showing four broadcast service objects, including pseudo-target service dissemination, area-notice service dissemination, environmental broadcast services, and tidal-window notices; (b) dissemination configuration and shore-based display, illustrating broadcast-area selection, message-priority setting, S-100-compatible message-field configuration, and pseudo-target information display in the shore-based system.

collection and analysis, no large-scale offline trajectory reconstruction or interpolation was performed in this study. Instead, real-time data-quality control and sample screening were adopted to ensure the reliability of the case analysis. During real-time monitoring, duplicated messages, records with missing or abnormal MMSI, invalid positions, obviously abnormal speed or course values, and vessels outside the predefined observation area near Areas 8 and 9 were excluded. Incomplete trajectories with insufficient observation duration, excessive time gaps, or too few valid AIS points were directly discarded. Based on AIS ship-type information and on-site VTS watchkeeping observations, fishing vessels, engineering vessels, anchored vessels, and other operational craft not directly related to the MASS-oriented VTS service scenario were also excluded. Therefore, only MASS-relevant cases that conformed to the assumed ANS decision-making logic are illustrated in this study.

5.1. Broadcasted VTS content for MASS at Yingkou Port

As no MASS are currently operating in Yingkou Port, closed-loop validation of MASS responses to VTS could not be conducted. Therefore, the Yingkou Port case is used in this study as a platform-based instantiation of the proposed framework in a real port environment, rather than as a full operational validation. Fig. 9 illustrates the detailed content of the broadcast VTS generated during the test run. The pseudo-target service provided dynamic information to ships operating in different water areas. The area notice service disseminated navigational information, including warning zones, prohibited anchoring areas, distress areas, and recommended routes within the jurisdictional waters of Yingkou Port. Environmental broadcast and tidal services supplied real-time hydrological and meteorological data for the ANS. The Yingkou-specific separation thresholds used in this study are documented in Section 4, together with the platform-based implementation results, providing context for the addressed-service interventions that follow.

5.2. Addressed VTS content for MASS

To illustrate the MASS-compliant port entry and exit behaviour using real traffic data, a target vessel is selected (MMSI: 413,241,520) was selected. As the vessel sequentially crossed monitoring line 1 and monitoring line 2, the shore-based VTS correctly detected the trigger conditions for the *Port Approach Control* and *Vessel Space Control* services, issuing addressed messages at 22:36 and 22:53, respectively. These messages are shown in the middle panel of Fig. 10 for port approach control and in the lower panel for space control. All messages were successfully delivered and displayed on the monitoring interface. They supported the permissions process and provided operational guidance, including recommended speed and required separation from the preceding vessel, thereby supporting safe navigation during subsequent berthing and unberthing operations.

The addressed VTS apply the port-specific spacing envelopes introduced in Section 4. Table 2 summarises the Yingkou Port thresholds aligned with the four collision-risk stages, providing concrete calibration points for operational deployment. In contrast to the other two services which trigger on entry and exit, the *collision avoidance control* operates as a continuous supervisory mechanism active throughout the remit of the VTS. The collision risk index (CRI) between vessel pairs are continuously evaluated and an event is triggered upon reaching the threshold. As illustrated in the Fig. 11, at 14:12 the CRI between the two vessels connected by the green line in the right panel is approximately 0.2, indicating a low collision risk. As the vessels converge, the CRI increases to 0.7 at 14:21 which puts it in the border of urgent or imminent danger situation. Upon exceeding the predefined risk threshold, the shore-based VTS issues an advisory service, providing guidance on velocity adjustment and route deviation to avoid the orange shaded risk area of the interface.

It should be noted that the addressed services illustrated in this section should not be interpreted as private instructions sent exclusively to a single MASS without contextual disclosure. In practical deployment, especially when MASS and conventional vessels coexist, an addressed advisory that may lead to manoeuvres materially affecting nearby traffic, such as speed reduction, course alteration, waiting, or route replanning, should be accompanied by appropriate contextual information sharing with relevant nearby vessels. Such information may be provided through broadcast VTS, conventional VHF voice communication, or other locally available communication channels. This allows the target MASS to receive structured and machine-interpretable information, while enabling surrounding human-operated vessels to maintain sufficient awareness of the MASS-related manoeuvring intention. At the same time, this does not mean that all MASS-related manoeuvring information should be broadcast to all vessels. Consistent with the information-management logic of e-Navigation, contextual disclosure should follow the principles of necessity, relevance, timeliness, and operational impact, so as to avoid excessive or irrelevant information that may increase the decision-making burden or cause confusion.

5.2.1. Timing analysis of addressed VTS for MASS

To identify the appropriate timing for issuing addressed Port Approach Control and Vessel Space Control services for MASS, this study analysed the timing of service delivery based on the trajectory of the same target vessel discussed above. As rule-consistent navigation is a key operational assumption for MASS equipped with autonomous navigation systems, this case provides a representative baseline for illustrating the operational applicability of the proposed dissemination framework.

The merging manoeuvre was performed in the presence of two vessels already navigating within the channel. When the target vessel crossed monitoring line 1, the admissible upper and lower speed envelopes for a safe merge are shown by the yellow and green curves in Fig. 12. With the exception of the initial approach phase, the observed speed profile of the target vessel (yellow) remained within these bounds, indicating that sufficient gaps ahead and astern could be maintained and that the merging operation was feasible under the local separation requirement. Consequently, the interval 22:22–22:25 is identified as the critical window for issuing an addressed VTS *Port Approach Control* message whenever the instantaneous speed deviates beyond the admissible envelope, enabling timely speed correction and preserving merge safety.

Following completion of the merging manoeuvre, the three ships transitioned into a sequential queuing formation for port entrance, where *ship spacing control* becomes essential. The collision risk level and inter-ship distances are shown in Fig. 13. The target vessel exhibited insufficient spacing relative to the preceding and following vessels at approximately 22:26 and 22:56, with its collision risk indicator reaching local maxima around 22:26 and 22:49. Using the predefined warning thresholds, the interval 22:48–22:49 is identified as the key timing window during which velocity and distance oriented addressed advisories should be issued to the involved vessels, and their navigational behaviour subjected to enhanced monitoring.

5.2.2. Analysis of high-risk collision avoidance scenario

As no MASS are currently in operational service within this area, conventionally manned vessels employed as surrogate samples for the analysis. On November 19th, 2024, a four-ship encounter with potential collision risk occurred in area 9 of the VTS zone (Fig. 4).

The encounter shown in Fig. 14 spans three time steps and illustrates the manoeuvring behaviour of multiple vessels. Ships A, B, and C were laterally staggered but simultaneously heading toward the breakwater entrance, while Ship D approached from the opposite direction. Fluctuations in the course of Ship D were observed during the encounter. Consequently, Ship C, as the closest vessel to the oncoming Ship D, was required to reduce speed until all four vessels had passed. This scenario

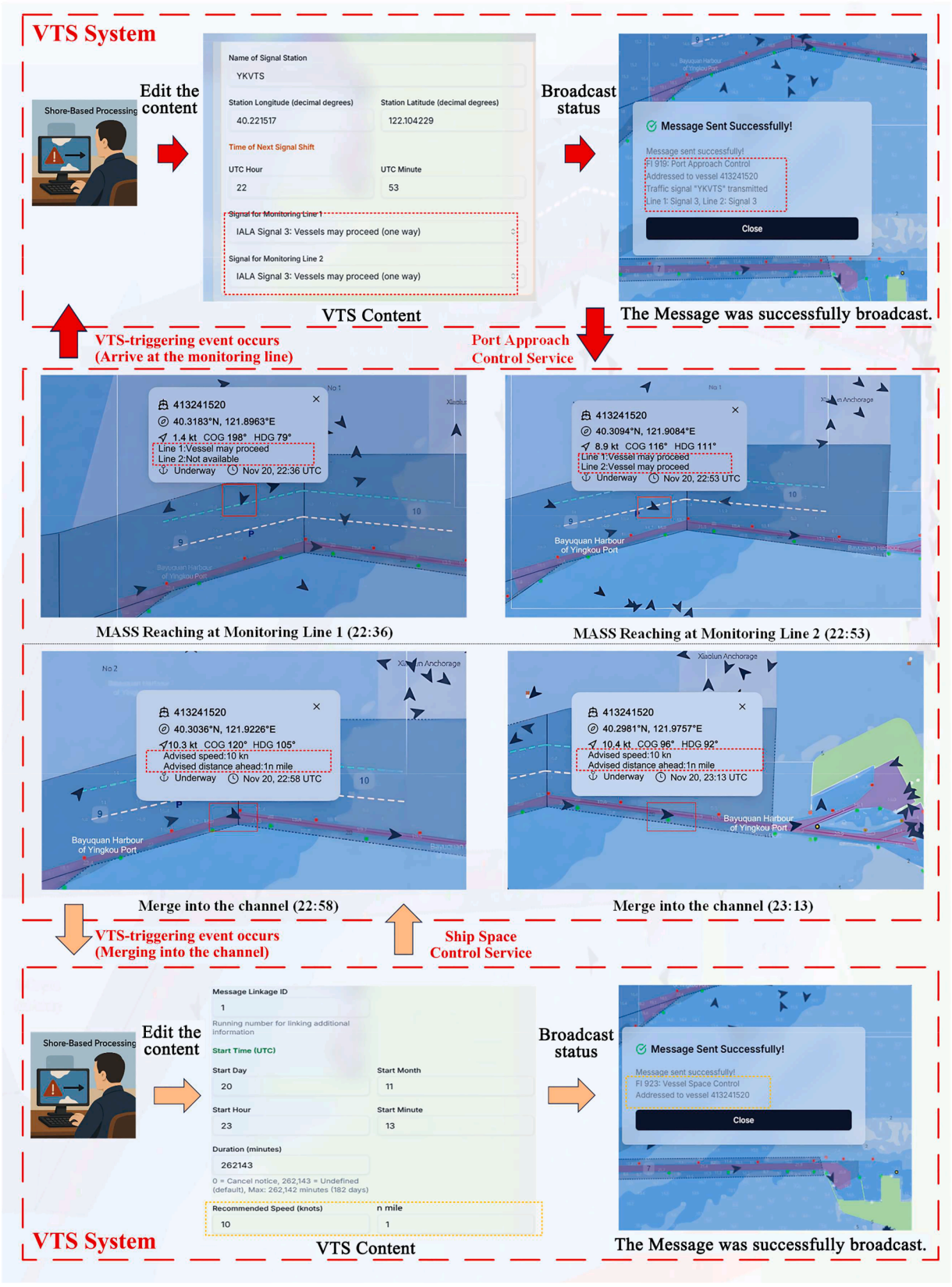


Fig. 10. Broadcast VTS content and message management interface: (1) broadcast coverage zones within the VTS area; (2) message priority levels to support filtering and scheduling; and (3) standardised, machine-readable mssage fields aligned with IHO S-100 and VDES delivery.

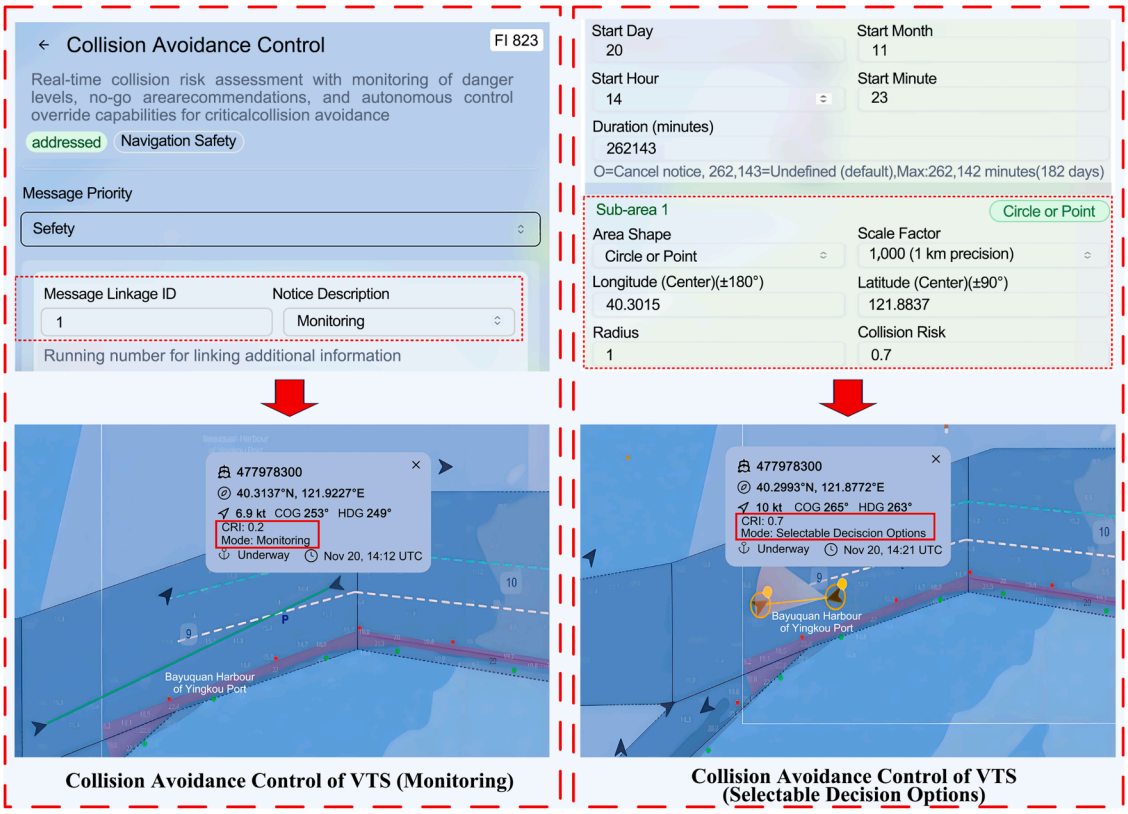


Fig. 11. Platform-based instantiation of addressed VTS services for collision avoidance control. (a) Monitoring service generated at a low collision-risk level, with the corresponding message fields and shore-based display; (b) selectable decision-option service generated when the collision risk increases.

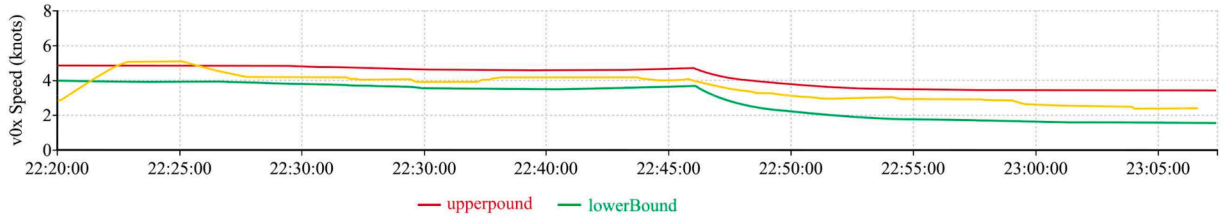


Fig. 12. Admissible velocity envelope for successful channel merging. The target vessel's speed must remain within the upper and lower bounds during the merge window to ensure a safe gap ahead and astern.

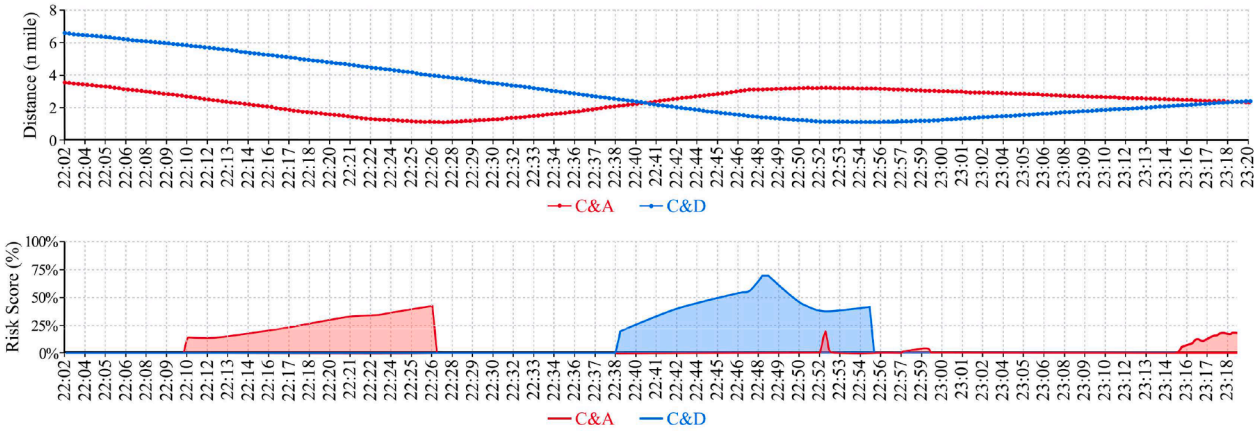
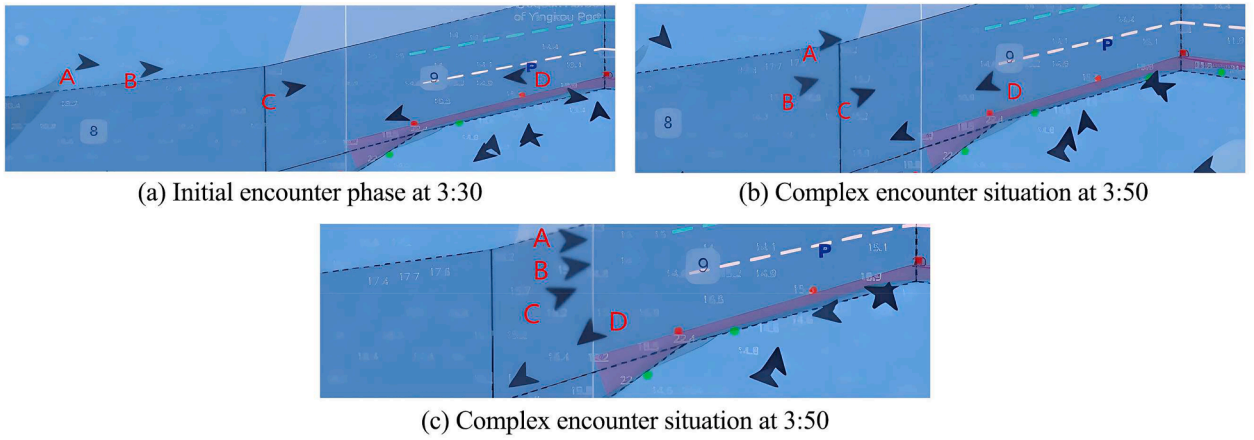


Fig. 13. Post-merging spacing parameters for the target vessel, showing forward and aft separation distances to adjacent vessels and the corresponding CRI used to flag unsafe separation and define addressed-advisory timing.



(a) Initial encounter phase at 3:30

(b) Complex encounter situation at 3:50

(c) Complex encounter situation at 3:50

Fig. 14. Multi-ship collision avoidance encounter scenario.

represents an objectively heightened collision-risk encounter.

In Fig. 15, it can be observed that Ship D performed a series of small-amplitude heading changes between 03:47 and 03:50. In the case that all the vessels were MASS, such manoeuvring fluctuations in Ship D, as shown in Fig. 15, could lead to misinterpretation during collision-avoidance interactions. This would increase the complexity of assessing Ship D's navigational intentions. In addition, The encounter is characterised by a lack of route harmonisation deemed necessary for mass operations, with vessels failing to merge smoothly into the channel along a recommended centreline. Instead, the uncoordinated approach shown in Fig. 14, combined with inadequate spacing control relative to the thresholds for Yingkou Port reported in Table 1, all elude to the key finding of the literature review of current VTS being overly geared towards conventional human interpretable ships. It is therefore critically important for shore-based operators to monitor vessel behaviour and enhance the predictability of all vessels within their remit when MASS are in the area.

In the context of proposed VTS for MASS, all vessels would have exchanged speed control sequence and planned trajectories. Vessel D would have been identified as a key monitoring target due to its pronounced manoeuvring fluctuations, with an appropriate risk level assigned and corresponding event-triggered services issued to the vessel. An examination of the target vessels' risk profiles metrics (Fig. 16) and the timing of VTS service provision under the event-triggered mechanism indicates that the VTS should have designated MASS D as a priority monitoring and intervention target at 03:47, clarified its intended manoeuvres, and, if necessary, issued addressed velocity area or vector recommendations or assumed control.

Furthermore, based on the vessel space-control thresholds adopted for Yingkou Port, the calculated values of the distance at the closest point of approach for MASS A, MASS B, and MASS C during their preceding manoeuvres were sufficiently small to pose a navigational risk. Accordingly, addressed advisory services should have been provided between 03:41 and 03:54, advising the vessels to maintain safe separation.

6. Conclusions

This study addresses the limitations of conventional VTS services when applied to MASS operations, particularly their insufficient machine interpretability of service content, unclear timing of information dissemination, and limited adaptability of service delivery modes. Accordingly, a MASS-oriented VTS framework is proposed. The framework focuses on VTS content design and information dissemination mechanism design, and is positioned at the shore-based service and architectural levels, rather than at the level of onboard autonomous navigation algorithm development or control performance optimisation.

The main theoretical contribution of this study is the machine-interpretable reformulation of conventional VTS. By converting information originally designed for human operators into structured and fine-grained service objects parsable by ANS, the proposed framework links shore-based VTS provision with the decision-making requirements of MASS. As it does not assume a specific ANS architecture, the framework is architecturally neutral and may support rule-based, learning-based, and hybrid ANS. Based on this reformulated service content, an event-triggered hybrid broadcast/addressed dissemination mechanism is further proposed. Broadcast services provide area-wide contextual information, whereas addressed services deliver vessel-specific messages triggered by navigation events or risk states. This mechanism helps reduce irrelevant and redundant information received by ANS and improves the adaptability of VTS to MASS operations. From a practical perspective, the proposed framework shows potential compatibility with IHO S-100-based data modelling and VDES-based service dissemination, providing an implementation pathway for the evolution of existing shore-based maritime service infrastructures towards machine-interpretable service delivery. This study instantiated the framework in Yingkou Port, demonstrating how the proposed VTS architecture, service content organisation, and hybrid broadcast/addressed dissemination mechanism can be applied in a specific port environment. The case-based instantiation indicates that the processes of service generation, event triggering, information configuration, and dissemination are

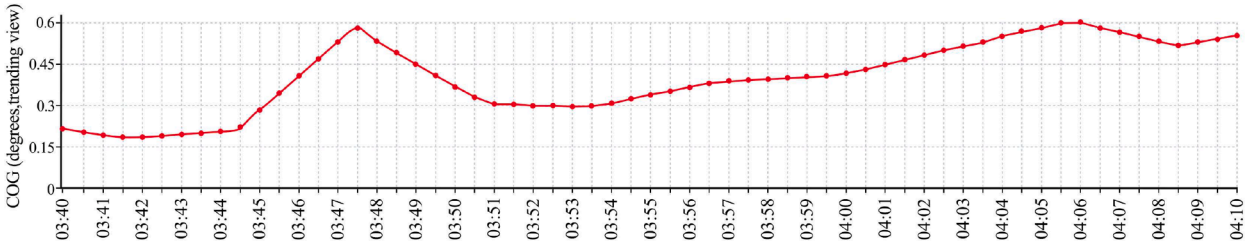


Fig. 15. Change in course and trajectory trend of ship D.

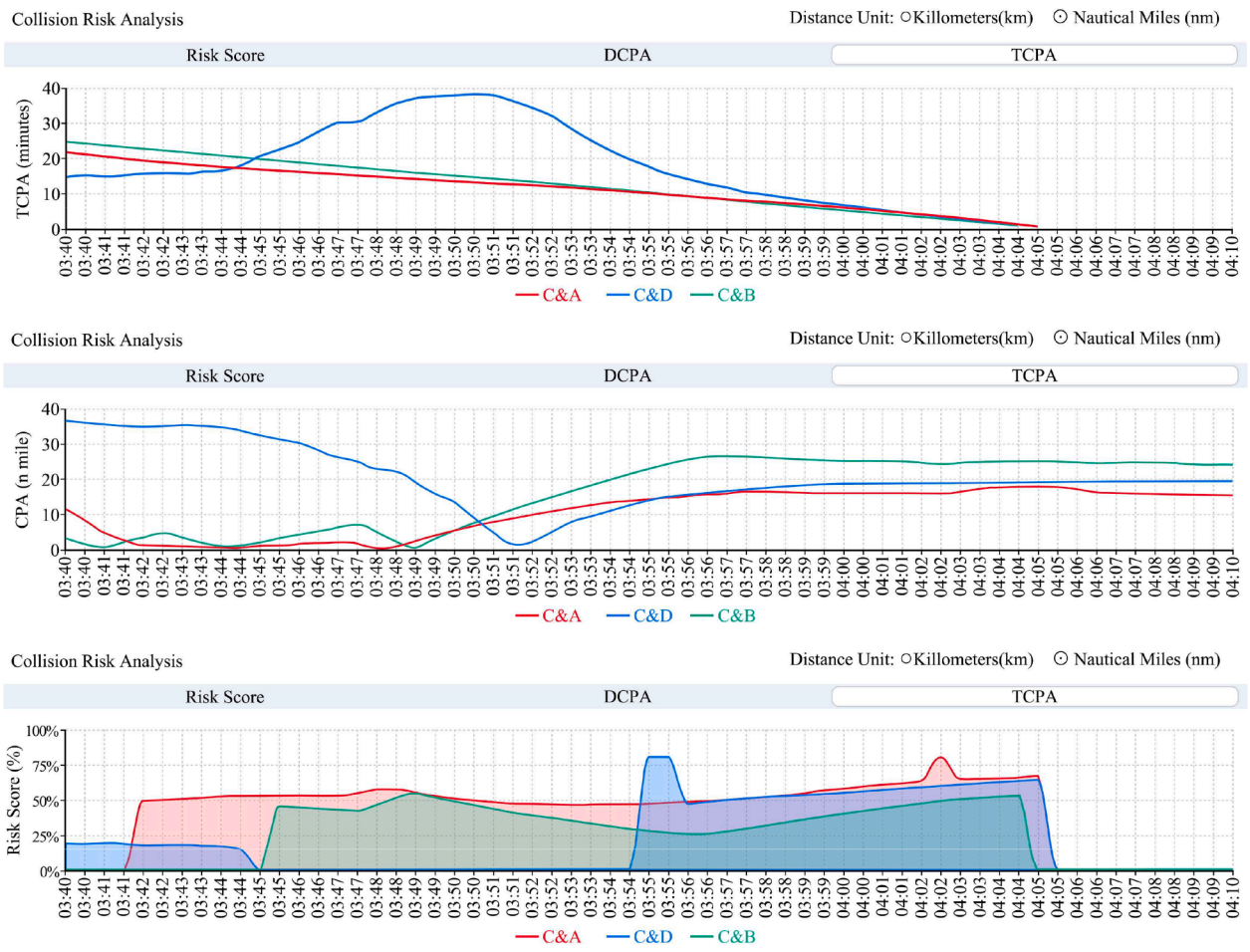


Fig. 16. Collision Risk Index (CRI), Closest Point of Approach (CPA), and Time to Closest Point of Approach (TCPA) of the four encountering ships.

feasible at the platform level.

This study still has several limitations. First, no operational MASS were available in Yingkou Port during the study period; therefore, closed-loop validation of how MASS receive, interpret, and respond to the proposed VTS services could not be conducted. Second, this study provides a platform-based implementation and demonstration rather than full operational validation with real MASS, and practical communication issues, such as communication latency, were not examined in depth. Third, the coordination between addressed services and surrounding conventional vessels in mixed traffic has not been fully investigated. Although addressed services can provide structured and vessel-specific information to MASS, manoeuvring intentions that may materially affect nearby traffic should be accompanied by appropriate contextual information sharing through broadcast VTS, conventional VHF communication, or other locally available channels. Finally, the proposed framework has so far been instantiated only in the Yingkou Port scenario, and its generalizability to busier ports, multi-directional traffic environments, or more complex operational settings remains to be further investigated.

Future research will extend the proposed framework to more complex waterways and operational MASS scenarios. Further work will focus on refining VTS service objects, formalising their correspondence with ANS decision-making requirements, and developing more proactive event-triggering mechanisms that account for temporal dependencies among navigation events, risk evolution, and causal factors. The coordination between addressed VTS services and surrounding conventional vessels will also be further investigated, particularly in terms of communication transparency, cooperative manoeuvre negotiation, and multi-vessel information sharing. Real MASS trials, hardware-in-the-loop experiments, simulation-in-the-loop experiments, and comparisons with baseline dissemination strategies will be conducted to assess the applicability and robustness of the framework under diverse port, mixed-traffic, and communication conditions.

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CRediT authorship contribution statement

Muzhuang Guo: Writing – original draft, Methodology, Funding acquisition, Data curation, Conceptualization. **Hongze Liu:** Visualization, Software. **Min Zhang:** Methodology, Data curation. **Zhengjiang Liu:** Methodology, Conceptualization. **Nana Kutin:** Writing – original draft, Methodology. **Peng Wu:** Conceptualization. **Zaili Yang:** Supervision, Methodology, Conceptualization. **Yuanchang Liu:** Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.apor.2026.105256.

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