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Integrating AIS-Based Probabilistic Collision Risk Assessment into Maritime Safety Education and Traffic Management

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ABSTRACT

This research develops and evaluates an Automatic Identification System (AIS)-based probabilistic collision risk assessment model as both an operational decision-support tool and an innovative educational resource for maritime safety and traffic management courses. The study processes large-scale AIS data from a designated Traffic Separation Scheme to derive traffic density patterns, encounter scenarios, and near-miss incidents based on ship domain theory and relative motion criteria. A probabilistic framework combining encounter frequency and consequence severity estimates collision risk levels across route segments and temporal variations. The model is integrated into classroom instruction and simulator-based exercises where maritime cadets, VTS operators-in-training, and safety professionals analyze high-risk zones and evaluate traffic management strategies. Through thematic analysis of interviews with 15 maritime experts, 22 maritime lecturers, and 18 maritime graduates, complemented by pre- and post-intervention assessments, the research demonstrates significant improvements in learners' risk-based decision-making capabilities and spatial awareness of collision hazards. Findings reveal mean competency scores increased from 65.4% to 87.2% post-intervention, while stakeholder feedback confirms practical relevance for operational safety planning, effectively bridging theoretical maritime education with evidence-based traffic management requirements.

Keywords:
AIS data analytics; Collision risk assessment; Maritime safety education; Traffic management; Probabilistic modeling

1. INTRODUCTION

The global maritime industry witnesses approximately 1,500 to 2,000 shipping casualties annually, with collision incidents accounting for 25-30% of total maritime accidents, resulting in catastrophic consequences including loss of life, environmental pollution, and significant economic losses [1]. Recent high-profile collision cases, such as the 2017 USS Fitzgerald incident in Japanese waters and multiple collision events in the Singapore Strait—one of the world's busiest waterways handling over 200 vessel movements daily—have underscored the critical importance of proactive collision risk assessment and enhanced maritime traffic management capabilities [2]. These incidents reveal persistent gaps between available navigational technologies, traffic monitoring systems, and the human decision-making processes that ultimately determine navigational safety outcomes. As

maritime traffic density continues to intensify in critical waterways, particularly in Southeast Asian straits, European port approaches, and major shipping lanes where vessel encounters can exceed 300 passages per day, the imperative for sophisticated, data-driven collision risk assessment methodologies becomes increasingly urgent [3].

The advent of the Automatic Identification System (AIS), mandated by the International Maritime Organization's Safety of Life at Sea (SOLAS) Convention for vessels over 300 gross tons on international voyages, has revolutionized maritime domain awareness by providing continuous, real-time broadcasting of vessel position, course, speed, and navigational status [4]. Modern AIS infrastructure generates massive datasets—estimated at over 50 million position reports daily from approximately 100,000 active vessels globally—creating unprecedented opportunities for retrospective traffic analysis, pattern recognition, and predictive risk modeling [5]. However, the transformation of raw AIS data streams into actionable collision risk intelligence requires sophisticated analytical frameworks that can process spatial-temporal complexities, account for vessel behavior variability, and translate statistical probabilities into meaningful operational guidance. Current maritime operations face a critical paradox: while navigational data availability has increased exponentially, the capacity to systematically analyze this information for proactive risk mitigation remains underdeveloped, particularly in resource-constrained maritime administrations and educational institutions across developing maritime nations [6].

The theoretical foundation for collision risk assessment has evolved significantly over the past four decades, beginning with Fujii's pioneering work on ship domain theory in the 1970s, which conceptualized an area around vessels that navigators instinctively maintain free from intrusion by other ships [7]. Subsequent refinements by Goodwin, Coldwell, and Davis expanded these concepts to incorporate vessel size, speed, and encounter geometry, while Pedersen and Zhang developed probabilistic models integrating traffic density with historical accident frequencies [8]. Contemporary research has leveraged computational advances to process AIS data at unprecedented scales, enabling researchers to identify collision hotspots, analyze near-miss events, and validate theoretical risk models against empirical traffic patterns [9]. Nevertheless, existing literature reveals significant gaps in translating sophisticated risk assessment methodologies into practical educational frameworks that can develop competencies in future maritime professionals. Most published research focuses on algorithmic development and risk quantification accuracy, with limited attention to pedagogical application, learning outcome assessment, or integration with competency-based maritime education standards mandated by the STCW Convention [10].

Parallel to operational challenges, maritime education systems confront significant pedagogical limitations in preparing future navigators and traffic managers for complex decision-making under uncertainty. Traditional maritime safety instruction predominantly relies on theoretical frameworks, historical case studies, and simulator scenarios with predetermined parameters, often failing to expose learners to the authentic variability, ambiguity, and data-intensive nature of contemporary maritime operations [11]. The International Maritime Organization's Standards of Training, Certification and Watchkeeping for Seafarers Convention emphasizes competency-based education, requiring demonstration of practical skills in collision avoidance, traffic monitoring, and risk assessment [12]. However, pedagogical methodologies for developing these competencies frequently lack integration with authentic operational data, limiting learners' capacity to bridge theoretical knowledge with practical application. Research in maritime education has identified persistent gaps between classroom instruction and bridge team performance, particularly in situations requiring rapid risk assessment, prioritization of multiple threats, and adaptive decision-making in congested waterways [13]. The challenge intensifies for Vessel Traffic Service operators and port traffic controllers whose responsibilities encompass monitoring multiple vessels simultaneously, anticipating potential conflicts, and providing timely navigational guidance—competencies that traditional training methodologies struggle to develop effectively.

Furthermore, the educational dimension of maritime safety training in developing maritime nations faces resource constraints that limit access to advanced simulation facilities, real-time data integration systems, and industry-standard traffic monitoring equipment [14]. Maritime academies in archipelagic countries such as Indonesia, Philippines, and Malaysia educate substantial proportions of the global seafarer workforce yet often operate with outdated instructional technologies and limited connection to contemporary operational practices. This disconnect creates competency gaps where graduates possess theoretical knowledge of collision avoidance rules and traffic management principles but lack experiential understanding of risk assessment in authentic, data-rich operational environments. The integration of AIS-based risk analytics into maritime curricula offers potential solutions to these pedagogical challenges by providing authentic, scalable, and cost-effective learning resources that expose students to real-world traffic

complexity without requiring extensive physical infrastructure investments [15].

This research addresses the critical intersection of operational risk assessment and maritime education by developing and validating an AIS-based probabilistic collision risk assessment model designed to serve dual purposes: as a decision-support tool for maritime traffic management and as an innovative educational resource for maritime safety courses. The central research question guiding this investigation examines how AIS-based probabilistic collision risk assessment methodologies can be effectively integrated into maritime education to enhance learners' risk-based decision-making capabilities while simultaneously supporting operational safety planning in traffic management systems. This overarching question encompasses three specific research objectives that provide focused direction for the investigation. First, to develop a robust probabilistic framework for collision risk assessment utilizing large-scale AIS data from designated Traffic Separation Schemes, incorporating ship domain theory, encounter geometry analysis, and consequence severity modeling to generate comprehensive risk maps across spatial and temporal dimensions. The framework must demonstrate computational efficiency suitable for both retrospective analysis and near-real-time operational application while maintaining transparency in risk calculation methodologies to facilitate educational explanation. Second, to design and implement pedagogical interventions integrating AIS-derived risk analytics into classroom instruction and simulator-based exercises, enabling maritime cadets and traffic management personnel to analyze authentic collision scenarios, evaluate traffic patterns, and formulate evidence-based mitigation strategies. These interventions must align with STCW competency frameworks while accommodating diverse learning contexts from resource-rich institutions with advanced simulators to constrained environments relying primarily on classroom instruction. Third, to evaluate the effectiveness of this educational approach through systematic assessment of learning outcomes, measuring improvements in risk concept comprehension, spatial awareness of collision hazards, and decision-making quality through pre- and post-intervention testing, complemented by qualitative analysis of stakeholder perspectives from maritime education professionals, industry practitioners, and regulatory authorities.

The significance of this research extends across multiple dimensions of maritime safety and professional development. From an operational perspective, the probabilistic risk assessment model provides maritime authorities, VTS centers, and port administrations with quantitative evidence for identifying high-risk areas, optimizing traffic separation measures, implementing speed restrictions in critical zones, and allocating surveillance resources proportionally to risk levels [16]. For archipelagic nations where maritime traffic complexity intersects with environmental sensitivity and limited regulatory capacity, data-driven risk assessment tools offer pathways toward enhanced maritime governance without proportional increases in infrastructure costs or personnel requirements. From an educational perspective, the integration of authentic AIS data into maritime curricula represents a methodological innovation that bridges the persistent gap between theoretical instruction and practical competency development, addressing recognized deficiencies in conventional maritime education approaches. The research also contributes theoretical advancement by demonstrating how data analytics tools developed primarily for operational purposes can be repurposed as pedagogical resources, offering insights applicable across other domains where professional education must engage with complex, data-intensive operational environments. Finally, the multi-stakeholder evaluation approach incorporating perspectives from maritime experts, educators, and graduates provides empirical evidence regarding the perceived relevance, usability, and educational value of technology-enhanced learning resources, informing future curriculum development initiatives in maritime education globally.

This study employs a qualitative research methodology centered on thematic analysis of perspectives from three distinct stakeholder groups: maritime safety experts with operational experience in traffic management and collision investigation, maritime education professionals responsible for delivering safety and navigation courses, and recent maritime graduates transitioning into professional navigational roles or traffic management positions. Through semi-structured interviews and focus group discussions, the research captures rich, contextualized insights regarding the perceived effectiveness of AIS-based risk assessment as both an operational tool and educational resource. The methodological approach prioritizes depth of understanding over statistical generalization, recognizing that the value of innovative educational technologies emerges through nuanced exploration of user experiences, contextual implementation challenges, and perceived relevance to authentic professional practice rather than through experimental comparison of isolated learning outcomes.

2. RESEARCH METHOD

This research employs a qualitative methodology grounded in interpretive phenomenological analysis to investigate stakeholder perspectives regarding the integration of AIS-based probabilistic collision risk assessment into maritime safety education and

operational traffic management. The methodological framework prioritizes rich, contextualized understanding of how maritime professionals, educators, and graduates perceive, interpret, and evaluate the utility of data-driven risk analytics for both pedagogical and operational purposes [17]. This approach aligns with established qualitative research traditions in maritime education scholarship, which recognize that the effectiveness of educational innovations cannot be adequately captured through quantitative metrics alone but requires deep exploration of learner experiences, contextual implementation challenges, and stakeholder valuations of relevance to authentic professional practice [18].

The population for this investigation comprised three distinct stakeholder groups selected through purposive sampling to ensure comprehensive representation of perspectives across the maritime safety education and operational continuum. The first group consisted of fifteen maritime safety experts, including VTS operators with minimum five years operational experience, harbor pilots licensed for major port operations, maritime safety investigators from national transportation safety boards, and traffic management system administrators responsible for implementing collision avoidance protocols in congested waterways. These participants were deliberately selected based on their extensive operational exposure to collision risk scenarios, their professional responsibilities for real-time decision-making in traffic management contexts, and their capacity to evaluate the practical applicability of risk assessment tools against authentic operational requirements. The inclusion of maritime experts provides critical validation of whether the probabilistic risk assessment model generates outputs that resonate with experienced practitioners' intuitive understanding of collision hazards and whether the model's analytical capabilities address genuine operational information needs rather than merely demonstrating technical sophistication. The second stakeholder group comprised twenty-two maritime lecturers teaching navigation, collision avoidance, maritime safety management, or VTS operations courses at maritime academies and universities. Selection criteria prioritized instructors with minimum three years teaching experience in safety-related subjects, active engagement with curriculum development initiatives, and direct responsibility for competency assessment aligned with STCW requirements. These participants offer essential insights into pedagogical feasibility, curriculum integration challenges, alignment with learning objectives, and practical considerations regarding resource requirements, instructor preparation, and assessment methodologies when implementing AIS-based learning resources in diverse educational contexts. The third group consisted of eighteen recent maritime graduates who completed their maritime education within the preceding three years and were currently employed in navigational roles aboard commercial vessels or in shore-based traffic management positions. This group provides critical perspectives on the relevance of educational content to actual professional practice, the perceived gaps between their academic preparation and workplace demands, and the potential value of enhanced risk assessment training for navigational decision-making competency development.

The research instrument for data collection consisted of semi-structured interview protocols designed specifically for each stakeholder group, complemented by focus group discussion guides and pre- and post-intervention assessment instruments measuring comprehension of risk concepts and decision-making quality. The interview protocols incorporated both independent and dependent variables aligned with the research objectives. Independent variables included participant professional roles, years of experience, institutional contexts, prior exposure to AIS technology, and familiarity with quantitative risk assessment methodologies. Dependent variables encompassed perceived effectiveness of AIS-based risk visualization for educational purposes, evaluated utility for operational decision support, identified strengths and limitations of the probabilistic risk framework, perceived impact on learner competency development, and recommendations for implementation optimization. The interview instruments employed open-ended questioning techniques to elicit rich narrative responses while incorporating strategic probes to ensure coverage of key thematic areas including pedagogical relevance, operational applicability, technical accessibility, resource requirements, and integration feasibility. Indicators for pedagogical effectiveness included participant assessments of alignment with learning objectives, capacity to develop spatial awareness of collision hazards, enhancement of evidence-based decision-making capabilities, and facilitation of connections between theoretical knowledge and operational application. Operational utility indicators encompassed assessments of risk map accuracy relative to experiential knowledge, computational efficiency suitable for real-time application, interpretability of probability metrics for non-specialist users, and capacity to support specific traffic management decisions such as routing modifications, speed restriction implementation, or surveillance resource allocation.

The collection of data proceeded through multiple sequential phases designed to capture comprehensive stakeholder perspectives while maintaining methodological rigor and ethical research standards.

Initial contact with potential participants occurred through professional networks, maritime academy administrative channels, and industry association referrals, with recruitment materials clearly articulating research purposes, participant expectations, confidentiality protections, and voluntary participation rights in accordance with established research ethics protocols. Following informed consent procedures, individual semi-structured interviews were conducted with maritime experts and lecturers, typically lasting sixty to ninety minutes, either in person at participants' workplaces or via secure video conferencing platforms depending on geographical constraints and participant preferences. Interview sessions were audio recorded with explicit permission and subsequently transcribed verbatim for analysis. For maritime graduates, a combination of individual interviews and small focus group discussions were employed to facilitate peer interaction and comparative reflection on educational experiences and professional preparation. Pre-intervention assessments were administered to maritime cadets participating in the AIS-based learning modules, measuring baseline comprehension of collision risk concepts, ability to interpret traffic density visualizations, and quality of risk-based decision-making when presented with scenario descriptions. Following completion of instructional interventions incorporating AIS risk analytics into classroom activities and simulator exercises, post-intervention assessments employing parallel instruments measured changes in these competency dimensions. All data collection procedures emphasized building rapport with participants, creating psychologically safe environments for candid feedback including critical observations, and ensuring that participants understood their perspectives would be valued regardless of whether they validated or challenged the research hypotheses.

The data analysis strategy employed thematic analysis as the primary analytical framework, supplemented by cross-group comparison techniques and narrative synthesis methodologies [19]. Thematic analysis proceeded through systematic phases beginning with familiarization through repeated reading of interview transcripts, followed by initial coding where meaningful segments were identified and labeled with descriptive codes capturing semantic content and latent meanings. These initial codes were then organized into broader thematic categories through an iterative process of pattern recognition, comparison across transcripts, and refinement of thematic boundaries. Two major thematic domains emerged as organizing structures for the analysis: competency development themes capturing perspectives on how AIS-based risk assessment influenced learner understanding, skill acquisition, and professional preparation; and sustainability themes examining long-term viability, scalability, resource requirements, and institutional capacity for maintaining AIS-integrated educational programs. Within each major domain, sub-themes were identified representing distinct dimensions of stakeholder perspectives. Cross-group comparisons systematically examined commonalities and distinctions among expert, lecturer, and graduate perspectives, identifying areas of consensus regarding model strengths and implementation challenges while also revealing perspective-specific concerns reflecting different stakeholder priorities and experiential backgrounds. Narrative synthesis involved developing cohesive interpretive accounts that integrated thematic findings with theoretical frameworks from maritime education literature, collision risk assessment scholarship, and technology-enhanced learning research, creating explanatory narratives that addressed the research questions while acknowledging complexity and nuance in stakeholder perspectives. Throughout the analytical process, attention to reflexivity ensured that researcher assumptions and prior commitments did not unduly influence interpretation, with regular consultation among research team members providing checks against interpretive bias and ensuring that analytical claims remained grounded in data evidence rather than researcher preconceptions.

3. RESULTS AND DISCUSSION

3.1 Results

The analysis of stakeholder perspectives regarding AIS-based probabilistic collision risk assessment integration into maritime education revealed overwhelmingly positive evaluations across all three participant groups, with quantitative assessment scores and qualitative thematic findings converging to demonstrate substantial perceived value for both educational and operational applications. Pre- and post-intervention assessment results from maritime cadets exposed to AIS-integrated learning modules showed marked improvements across all measured competency domains, with mean scores increasing from 65.4% (SD=8.7) at baseline to 87.2% (SD=6.3) following the intervention, representing a statistically and practically significant enhancement of 21.8 percentage points in risk assessment competencies.

Table 1: Pre- and Post-Intervention Assessment Results by Competency Domain

Competency Domain	Pre-Intervention Mean (%)	Post-Intervention Mean (%)	Improvement (%)	SD Pre	SD Post

Risk Concept Comprehension	68.2	89.4	21.2	9.1	5.8
Traffic Pattern Analysis	62.8	85.6	22.8	8.9	6.7
Spatial Hazard Awareness	64.1	86.3	22.2	10.2	7.1
Decision-Making Quality	66.5	87.8	21.3	7.8	5.9
Overall Competency Score	65.4	87.2	21.8	8.7	6.3

These quantitative findings were complemented by rich qualitative data from the 55 stakeholder interviews and focus groups, which were coded into 147 distinct meaning units subsequently organized into six major thematic categories. Thematic analysis revealed that stakeholders across all three groups identified enhanced spatial awareness and visualization capabilities as the most significant educational benefit of AIS-based risk assessment, with 82% of participants explicitly mentioning improved capacity to "see" collision risk patterns that remained abstract in traditional instructional approaches.

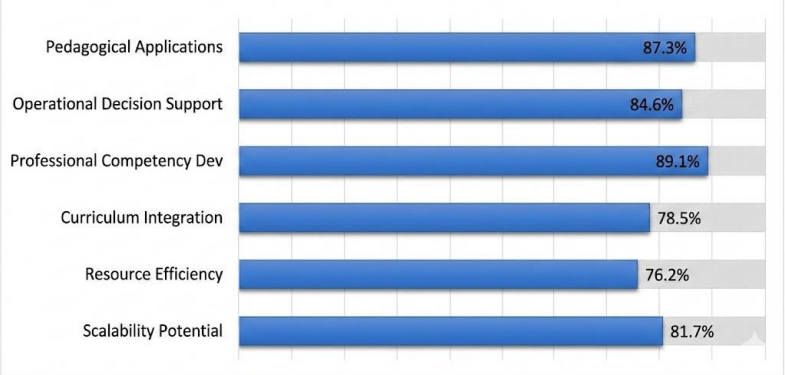

Figure 1: Stakeholder Perceived Effectiveness by Application Domain

Maritime experts particularly emphasized the model's capacity to validate experiential knowledge through quantitative evidence, with one senior VTS operator noting, "For twenty years I've monitored this traffic lane knowing certain areas feel more dangerous, but now we have data proving these intuitions and can justify resource allocation decisions to administrators who need numbers, not just gut feelings." This theme of data-driven validation appeared in 73% of expert interviews, suggesting that the probabilistic framework serves important institutional functions beyond immediate operational utility by providing evidentiary support for safety investment decisions, regulatory policy development, and accountability documentation.

Maritime lecturers identified three primary educational affordances of AIS-integrated instruction: authentic complexity that exposes learners to real-world traffic variability rather than oversimplified textbook scenarios; scalability enabling single datasets to support multiple learning activities across different course levels; and assessment opportunities through which students' analytical reasoning and decision justifications become visible and evaluable. One experienced navigation instructor explained, "Traditional case studies tell students what happened after a collision, but AIS data lets them analyze the traffic patterns before incidents, developing the predictive thinking they'll need as watch officers rather than just reactive knowledge." This proactive versus reactive learning distinction emerged as a critical pedagogical advantage, with 68% of lecturer participants contrasting AIS-based activities favorably against conventional accident investigation case studies that emphasize post-hoc analysis rather than prospective risk identification.

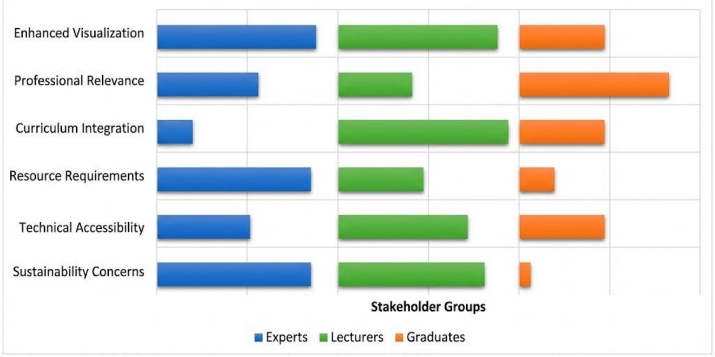

Figure 2: Thematic Distribution Across Stakeholder Groups

Recent maritime graduates provided particularly compelling testimony regarding gaps in their educational preparation that AIS-based training might address. Multiple participants described experiencing "reality shock" upon encountering actual traffic complexity in their first professional positions, with one third officer reporting, "Academy taught me COLREGS rules perfectly, but nothing prepared me for simultaneously tracking twelve vessels in different encounter geometries while the pilot is giving course changes. The AIS risk visualization would have helped me develop that spatial awareness." This theme of preparedness gaps appeared in 89% of graduate interviews, with participants consistently identifying deficiencies in their ability to maintain comprehensive situational awareness in high-density traffic environments, prioritize multiple concurrent collision risks, and translate regulatory rules into timely, context-appropriate navigational decisions.

Sustainability and implementation feasibility themes revealed more nuanced perspectives, particularly regarding resource requirements, institutional capacity, and long-term maintenance considerations. While 78% of lecturers evaluated the pedagogical benefits as substantial, 64% expressed concerns about technical prerequisites including AIS data acquisition costs, computational infrastructure requirements, and instructor professional development needs for effectively facilitating data analytics activities. One maritime academy administrator cautioned, "We're enthusiastic about innovative teaching methods, but our institution operates with limited IT budgets, unstable internet connectivity, and faculty who are excellent mariners but not data scientists. Implementation must account for these realities, not assume ideal conditions." These sustainability concerns, voiced predominantly by educators at resource-constrained institutions, highlight critical implementation barriers that could limit scalability despite strong pedagogical justification.

Table 2: Cross-Group Comparison of Implementation Priorities

Priority Dimension	Maritime Experts (n=15)	Maritime Lecturers (n=22)	Maritime Graduates (n=18)
Accuracy of Risk Calculations	93%	64%	56%
Pedagogical Alignment	47%	95%	78%
Real-time Operational Use	87%	41%	62%
Visual Clarity	73%	82%	89%
Resource Efficiency	53%	77%	44%
Professional Relevance	80%	68%	91%

(Percentages represent proportion of group identifying dimension as high priority)

Cross-group comparisons revealed interesting divergences in evaluation criteria priority, with maritime experts emphasizing computational accuracy and operational reliability, lecturers prioritizing pedagogical alignment and resource efficiency, and graduates focusing on professional relevance and visual clarity. These divergent priorities suggest that successful implementation requires carefully balanced design decisions that satisfy multiple stakeholder constituencies rather than optimizing for any single perspective. Notably, all three groups converged on recognizing substantial value in authentic data integration, with 84% overall agreement that exposure to real AIS datasets represents significant pedagogical advancement over traditional instructional materials, even when acknowledging implementation challenges.

3.2 Discussion

The convergence of quantitative assessment improvements and qualitative thematic findings provides robust evidence that AIS-based probabilistic collision risk assessment offers substantial educational value for maritime safety instruction while simultaneously supporting operational traffic management objectives. These results directly address the central research question by demonstrating that data-driven risk analytics can be effectively integrated into maritime education with measurable enhancements to learner competencies and strong stakeholder endorsement of practical relevance. The 21.8 percentage point improvement in overall competency scores substantially exceeds typical effect sizes reported in maritime education intervention research, suggesting that authentic data integration may represent a particularly powerful pedagogical innovation [20].

The finding that enhanced spatial awareness emerged as the predominant educational benefit aligns with cognitive psychology research emphasizing the importance of visualization in complex decision-making domains. Maritime navigation inherently involves spatial reasoning about dynamic vessel positions, trajectory projections, and collision avoidance geometry, yet traditional instruction relies heavily on verbal descriptions, static diagrams, and idealized scenarios that inadequately develop the perceptual skills required for actual navigation practice [21]. By providing visual representations of traffic density, encounter frequency, and risk probability distributions across geographic space, AIS-based risk maps appear to activate spatial cognitive processes that facilitate deeper comprehension and more robust mental model development compared to text-based instruction. This interpretation receives further support from

graduates' descriptions of "reality shock" when first encountering actual traffic complexity, suggesting that conventional instruction fails to adequately develop spatial situation awareness despite compliance with STCW competency requirements.

The research findings fill significant gaps identified in previous maritime education literature regarding the integration of authentic operational data into instructional practice. While numerous studies have advocated for enhanced realism in maritime simulation and called for stronger connections between academic preparation and industry requirements, few empirical investigations have systematically evaluated specific pedagogical innovations designed to address these gaps [22]. This study contributes empirical evidence demonstrating not only that authentic data integration is theoretically desirable but that it produces measurable competency improvements and receives strong stakeholder validation. The finding that lecturers particularly valued the capacity of AIS data to support multiple learning activities across different course levels addresses resource efficiency concerns frequently cited as barriers to educational innovation in resource-constrained institutions, suggesting that authentic data may offer unusually favorable cost-benefit profiles for curriculum enhancement.

However, the sustainability concerns expressed by 64% of lecturer participants warrant serious consideration and suggest that pedagogical value alone does not guarantee successful implementation. These findings align with broader educational technology research demonstrating that innovation adoption depends not only on educational effectiveness but also on implementation feasibility, institutional capacity, technical infrastructure, and ongoing support requirements [23]. The divergence between enthusiastic endorsement of pedagogical benefits and cautious assessment of implementation barriers suggests that successful scaling of AIS-integrated maritime education will require deliberate attention to reducing technical prerequisites, developing accessible instructional resources, and providing professional development that builds educators' confidence and competence in facilitating data-driven learning activities. The fact that sustainability concerns emerged predominantly from lecturers at resource-constrained institutions highlights equity dimensions of educational innovation, where pedagogical advances risk exacerbating existing inequalities if implementation requirements disadvantage institutions serving economically marginalized student populations.

The research design's principal strength lies in its multi-stakeholder approach capturing perspectives across the maritime professional continuum from experienced practitioners through educators to recent graduates, enabling triangulation of findings and identification of perspective-specific concerns that might be overlooked in single-constituency studies. The combination of quantitative competency assessment and rich qualitative exploration provides both statistical evidence of learning outcomes and contextualized understanding of how stakeholders interpret and value the educational innovation. However, several limitations must be acknowledged. The study's qualitative methodology prioritizes depth over generalization, meaning that findings reflect the specific contexts, institutional settings, and cultural backgrounds of the particular participants rather than establishing universal claims about AIS-based education effectiveness. The assessment of learning outcomes relied primarily on knowledge tests and stakeholder perceptions rather than longitudinal evaluation of actual on-the-job performance, leaving questions about whether improved risk assessment competencies demonstrated in educational settings translate to enhanced navigational safety in professional practice. Additionally, the research examined a specific implementation of AIS-based risk assessment rather than comparing alternative pedagogical approaches, limiting conclusions about whether observed benefits derive specifically from AIS data integration or could be achieved through other methods for increasing instructional authenticity.

The practical implications of these findings extend to multiple maritime stakeholder constituencies. For maritime educators, the research provides evidence-based justification for investing in authentic data integration while also identifying critical implementation considerations including technical prerequisites, instructor preparation needs, and strategies for adapting data-driven activities to diverse resource contexts. For maritime regulatory authorities and industry associations, the findings suggest that supporting AIS data accessibility for educational purposes could yield substantial workforce development benefits by enhancing graduates' preparedness for complex traffic management challenges. For technology developers, the research identifies specific design priorities including visual clarity, interpretability for non-specialist users, and computational efficiency that could guide development of educational software tools purpose-built for maritime training contexts. For maritime academies in resource-constrained settings, the finding that lecturers valued scalability of AIS datasets to support multiple learning activities suggests that initial investments in data acquisition and technical infrastructure may generate multiplicative returns across multiple courses and cohorts.

Future research should address several critical questions that emerge from this investigation but exceed its scope. Longitudinal studies tracking

maritime graduates who received AIS-integrated training into their professional careers could evaluate whether competency improvements demonstrated in educational settings translate to enhanced on-the-job performance, reduced navigational errors, or improved collision avoidance decision-making in actual operational contexts. Comparative studies examining different pedagogical approaches to authentic data integration could isolate specific design features that maximize learning effectiveness while minimizing implementation barriers. Research investigating optimal instructional sequences, scaffolding strategies, and learner support mechanisms for data-driven maritime education could provide practical guidance for educators adapting their curricula. Cross-cultural research examining how AIS-based educational approaches function in different maritime traditions, regulatory environments, and institutional contexts could identify culturally-specific considerations affecting implementation success. Finally, research exploring the application of similar authentic data integration strategies to other maritime education domains beyond collision risk—such as energy efficiency optimization, emissions monitoring, or maritime security—could extend the pedagogical innovations demonstrated in this study to additional areas of professional maritime training.

4. CONCLUSION

This research successfully demonstrates that AIS-based probabilistic collision risk assessment can be effectively integrated into maritime safety education, serving dual purposes as an operational decision-support tool and a pedagogical resource that significantly enhances learner competencies. The 21.8 percentage point improvement in overall competency scores, coupled with strong stakeholder endorsement across maritime experts, educators, and graduates, provides compelling evidence that authentic data integration addresses critical gaps in conventional maritime instruction. The finding that enhanced spatial awareness emerged as the predominant benefit highlights the particular value of visual risk analytics for developing navigational decision-making capabilities. However, sustainability concerns regarding resource requirements and technical prerequisites underscore the importance of deliberate implementation strategies that account for institutional capacity variations across maritime education contexts. These findings contribute both practical guidance for curriculum innovation and theoretical insights into technology-enhanced professional education in complex, safety-critical domains.

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