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2026 Volume 4, Issue 2
Contemporary Education Frontiers
ISSN (Online): 3029-1860 ISSN (Print): 3029-1879

Application of AIS Data Analysis in Teaching of Collision Avoidance in Nautical Technology Specialty

Genyuan Wang, Guoguang Lu, Chuiyao Chen
School of Maritime, Hainan Vocational University of Science and Technology, Haikou 571126, Hainan, China

Abstract: Against the backdrop of deep integration between intelligent shipping and maritime data, the digital transformation of traditional maritime technology education has become an inevitable requirement for industry development. As the core resource documenting real-world vessel navigation behavior, Automatic Identification System (AIS) data holds irreplaceable value in analyzing collision avoidance decision-making logic and establishing objective quantitative teaching evaluation systems. This paper systematically reviews the research progress in the past five years, both domestically and internationally, on utilizing AIS data mining technology to identify collision avoidance scenarios, extract operational characteristics, and assess collision risks. It focuses on exploring application pathways of data analysis technologies in auxiliary maritime collision avoidance training, identifying core challenges and research gaps in current technical implementation scenarios. The study aims to provide theoretical foundations for vocational undergraduate programs to establish a "data-driven" collision avoidance teaching model, thereby fostering high-quality interdisciplinary maritime professionals equipped with data-driven thinking.

Keywords: AIS data analysis; navigation technology; collision avoidance instruction; vocational undergraduate education; teaching reform

Online publication: February 26, 2026

1. Introduction

As the global shipping industry accelerates its intelligent and digital transformation, both the International Maritime Organization (IMO) 's "e-Naving Strategy" and the "Guidelines for Intelligent Shipping Development" jointly issued by China's Ministry of Transport and other departments emphasize technological innovation and high-quality seafarer training as two core pillars for ensuring navigation safety. These documents particularly highlight the critical requirement of navigation data application capabilities for the new generation of seafarers. Against this backdrop, the training objectives for maritime technology professionals are undergoing fundamental adjustments, shifting from traditional specialized shipbuilding skills to cultivating compound talents with "traditional navigation competencies + data application mindset." In the era of intelligent shipping, seafarers must not only master traditional shipbuilding techniques and collision avoidance rules but also develop mature data application thinking to extract actionable information from massive navigation data centered on AIS (Automatic Identification System) for supporting collision avoidance decisions.

In alignment with the new talent development objectives, the traditional teaching model of the core course "Ship Maneuvering and Collision Avoidance" in maritime technology programs has demonstrated significant inadequacies.

Current collision avoidance instruction heavily relies on navigation simulator training, which, while capable of replicating preset scenarios, remains confined to isolated training with single scenarios and fixed operating conditions. The absence of real-world ship track data in the curriculum prevents students from fully understanding the complex and dynamic navigation environment of actual sea areas, nor does it facilitate the identification of collision avoidance decision-making patterns in real-world navigation. More critically, the existing training evaluation system still primarily depends on instructors 'subjective judgments and on-site observations, resulting in ambiguous assessment criteria and subjective evaluation standards. The lack of precise quantifiable metrics based on AIS data (such as closest encounter distance DCPA, closest encounter time TCPA, and evasive timing) undermines the fairness and consistency of evaluation outcomes. This also hinders the standardization of teaching feedback and fails to effectively enhance students' collision avoidance decision-making capabilities.

Existing authoritative reviews have systematically examined the application progress of AIS data mining and machine learning technologies in maritime fields[1], yet few studies focus on integrating AIS data analysis with collision avoidance education, particularly lacking specialized frameworks for vocational undergraduate education scenarios. Based on this, this paper systematically reviews domestic and international research advancements in AIS data analysis technology for ship collision avoidance, with emphasis on exploring its application pathways and practical value in navigation technology programs. Deep integration of AIS data analysis with collision avoidance training can drive a systematic transformation of traditional collision avoidance education from "experience-driven" to "data-driven." This approach not only addresses current pain points in collision avoidance teaching, enhances students' decision-making capabilities in complex scenarios, and establishes an objective quantitative evaluation system, but also aligns with the inevitable requirements of vocational undergraduate maritime education adapting to intelligent shipping industry development. It provides systematic theoretical references and practical foundations for constructing future ship collision avoidance decision-making training systems.

2. Research Status of Collision Avoidance Behavior Recognition and Risk Assessment Based on AIS Data

2.1. Identification and Judgment of Ship Encounters

Accurate identification of collision scenarios is fundamental to implementing the International Regulations for the Prevention of Collisions at Sea (COLREGs). Jiang Longhui et al.[2] proposed that extracting key parameters such as relative distance, relative bearing, and speed ratios from massive AIS spatiotemporal data can effectively reconstruct ship trajectories. Current research predominantly employs rule-driven algorithms that deeply integrate AIS dynamic information with Articles 13-15 of COLREGs (overrunning, head-on, and crossing situations). The prevailing technical approach involves: first synchronizing spatiotemporal data to match ship tracks, then determining collision types based on bearing angle thresholds. For complex waters like ports and narrow waterways, researchers have introduced the DBSCAN density clustering algorithm to automatically classify massive track patterns. This method identifies typical collision scenarios without preset rule thresholds, enabling automated scenario selection and labeling for student training. However, the clustering results lack direct mapping to collision prevention regulations, resulting in poor interpretability and limited applicability in basic education. The ability to extract structured scenarios from massive raw data serves as a critical bridge for transforming "real-world navigation cases" into "standardized teaching tasks." Relevant patent achievements have validated the feasibility of this technical approach in collision avoidance simulation training[3].

2.2. Quantitative Research on the Evaluation Index System of Collision Avoidance

Traditional collision avoidance teaching evaluations predominantly rely on instructors' on-site observations and subjective judgments, lacking objective and standardized quantitative criteria. A quantified evaluation framework centered on DCPA (Dynamic Collision Prevention Assessment) and TCPA (Time-Critical Collision Avoidance) should be established. Significant progress has been made in this field: DCPA reflects spatial safety in collision avoidance, while TCPA measures temporal urgency. These metrics not only serve as spatiotemporal geometric indicators but also provide quantitative representations of the "collision danger" assessment under COLREGS Article 7. In teaching applications, dynamic DCPA safety thresholds can be set based on navigation characteristics of open waters and narrow channels, guiding students to transcend rigid safety value perceptions and truly understand the relativity of "safe distance" in collision avoidance. Recent research has expanded evaluation dimensions by introducing indicators such as "avoidance timing" and "safe distance maintenance." Studies show that analyzing operational samples from AIS historical trajectories of skilled pilots can identify optimal avoidance timing distributions for specific waters. In vocational undergraduate education, these quantitative metrics transform abstract "navigation experience" into visualized data feedback, addressing the challenges of subjective and difficult-to-quantify decision-making assessments while ensuring objective and fair evaluation outcomes.

2.3. Development of Collision Risk Assessment Model

The collision risk assessment model serves as the core component of decision support systems in collision avoidance education. Current authoritative reviews have systematically categorized AIS-based ship collision risk assessment models into two major types: deterministic models and intelligent machine learning models[1]. Deterministic models: Primarily based on geometric collision avoidance theory, such as the Ship Domain model and Collision Risk Index (CRI) model. These models feature rigorous computational methods, making them suitable for foundational theoretical instruction in undergraduate programs to help students understand spatiotemporal collision avoidance boundaries. Machine learning models: With advancements in big data technology, risk prediction models based on Support Vector Machines (SVM), Bayesian networks, and deep learning have become increasingly sophisticated. These models can process nonlinear characteristics in AIS data, enabling early warnings of potential collision risks. While machine learning models effectively handle nonlinear collision risks in complex environments, their "black box" nature fails to clearly explain the underlying logic of avoidance decisions, often leading to cognitive confusion among students regarding the application of collision avoidance rules. To address this, existing research[4] proposes a hybrid architecture combining "deterministic models to establish rule logic and machine learning models to enhance environmental adaptability." This framework ensures both the interpretability of risk assessments—allowing students to accurately trace corresponding collision avoidance rule provisions—and the capability for early risk warnings in complex scenarios, fully meeting the core requirements of collision avoidance education.

The combination of the logic of deterministic model and the predictability of machine learning model can not only provide scientific decision-making assistance for students, but also provide the core algorithm support for the construction of "data-driven" training platform in teaching reform.

3. Application Exploration of Deep Integration between AIS Big Data Analysis and Navigation Teaching

3.1. Digitalization of Teaching Resources: Construction of "Living Textbook"

Traditional collision case teaching relies heavily on static diagrams or textual descriptions, making it difficult for students to intuitively grasp the spatiotemporal dynamics of collision avoidance decisions. By utilizing AIS historical trajectory data, the teaching team can recreate the real evolution of typical collision incidents like the "Sangji" vessel. Through AIS data, the complete dynamic process—including pre-accident speed fluctuations, heading changes, and the continuous reduction of DCPA—can be accurately reconstructed, forming an unalterable dynamic teaching case. Relevant research[5] confirms that such dynamic cases enable students to intuitively perceive the spatiotemporal dynamics of collision avoidance decisions, significantly enhancing their analytical skills in collision avoidance scenarios. This digitalization of teaching resources based on real voyage data allows students to analyze the root causes of operational errors from a holistic perspective, clarify the causal relationship between non-compliant operations and accidents, and effectively improve their ability to perceive complex navigational environments.

3.2. Differentiated Training of "Data Application Ability" for Vocational Undergraduates

For vocational undergraduate programs, the teaching focus should shift from the "black-box algorithm innovation" typical of research-oriented talents to enhancing "data application capabilities." The instructional approach should guide students to move beyond complex algorithmic logic and master the use of visualization tools. By introducing integrated AIS analysis workstations, students learn to interpret ship traffic flow characteristics and potential collision risks through dashboards and heat maps. This transition from "algorithmic black boxes" to "intuitive tools" precisely aligns with the technical application demands of composite crew members in the era of intelligent shipping.

3.3. Scientific Evaluation System: Constructing Quantitative Models

The objectivity of teaching evaluation has long been a core challenge in the reform of collision avoidance instruction. Existing research has developed a multi-dimensional quantitative evaluation model for student collision avoidance operations based on AIS data[3]. Under this model, each student's collision avoidance action (e.g., turning timing and amplitude) is compared with the "industry benchmark values" generated from massive AIS data. By calculating the DCPA/TCPA deviation between students' training trajectories and the industry benchmark trajectories derived from AIS data, the model evaluates three key dimensions: timeliness of initial actions, significance of turning amplitude, and rationality of re-course after clearance. This data-driven approach effectively avoids the subjectivity and randomness inherent in traditional teacher-based assessments, generating precise teaching feedback across multiple dimensions while standardizing the evaluation process and ensuring objective results.

3.4. Interdisciplinary Integration: The Empowering Role of Teachers in the Context of Big Data

As educators with expertise in big data, their core mission is to bridge the technological divide for maritime students. During practical training, interdisciplinary instructors guide students in mastering fundamental data preprocessing techniques—such as using simple logic to filter out "jumps" and outliers in AIS signals—helping them understand data limitations. By demonstrating the data derivation process behind decision support systems (DSS), they assist maritime students in establishing a closed-loop mindset of "data collection—cleaning—analysis—decision-making," achieving deep integration and mutual empowerment between big data technology and maritime professional skills.

4. Current Research Challenges and Future Prospects

While AIS data provides precise quantitative tools for maritime education, practical implementation still faces multiple challenges. First, technical bottlenecks persist: Real-time AIS data processing inherently involves delays, and the timeliness and accuracy of data remain suboptimal when handling collision avoidance decisions within extremely short time windows, such as in urgent situations. Unprocessed "drift" and false data in AIS signals may introduce biases into teaching evaluation models, potentially misleading students' decision-making. Second, the depth of educational implementation is insufficient. Given significant disparities in data literacy among vocational undergraduate students, the core challenge lies in seamlessly integrating complex algorithmic logic into core maritime courses without deviating from the fundamental goal of cultivating collision avoidance skills. This requires avoiding the risk of turning instruction into mere computer operation drills. The key lies in balancing technological tools with the essential teaching content of collision avoidance rules—a critical issue that interdisciplinary faculty teams must address through sustained exploration.

Looking ahead, research trends will focus on developing an intelligent training system that integrates virtual and real-world elements. Drawing on existing studies on virtual reality integration, future advancements could leverage AIS historical big data to drive VR simulator scene modeling, creating highly realistic immersive collision avoidance training environments. Through a closed-loop model where "AIS data informs decision-making while VR technology presents situational awareness,” massive real-world flight trajectory data can be deeply integrated with immersive 3D visual interactions. This approach not only addresses the disconnect between traditional training scenarios and real maritime conditions but also enables precise identification of students ‘competency gaps via personalized quantitative evaluation systems. Furthermore, it significantly enhances students’ emergency response capabilities and psychological resilience under extreme conditions, driving the evolution of collision avoidance education toward smarter and more personalized approaches.

5. Conclusion

This paper systematically reviews the research progress on AIS data mining, ship collision avoidance situation recognition, and the construction of quantitative evaluation system at home and abroad. It clarifies the core value of AIS data analysis technology in the construction of collision avoidance teaching resources, the improvement of students’ collision avoidance decision-making ability, and the perfection of teaching evaluation system. It also fills the research gap of the lack of systematic review on the integration and application of AIS data and navigation collision avoidance teaching.

Funding

2026 Hainan Vocational University of Science and Technology Teaching Reform Research Project “Research on the Training Path of Ship Collision Avoidance Decision-Making Ability Based on AIS Data Analysis” (Project No.: HKJG2024-24).

Disclosure statement

The author declares no conflict of interest.

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