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Study on Risk Identification and Prevention and Control Measures for the Transportation of Hazardous Goods by Ships

Xiang Huang, Minghao Hu, Jiabo Chen

Jiangsu Maritime Institute, Nanjing, Jiangsu 211170, China

ABSTRACT

The transportation of hazardous goods by ships is a core link in the global supply chain. Its risks are characterized by suddenness, diffusibility, and high harmfulness. Once an accident occurs, it will cause catastrophic consequences to personal safety, marine ecology, and the shipping economy. Based on the four-dimensional analysis framework of "Man-Machine-Environment-Management", this paper systematically identifies the core risk points in the entire process of consignment, packing, navigation, unloading, and emergency disposal of hazardous goods by ships, and in-depth analyzes the technical bottlenecks, management loopholes, and external incentives that breed risks. By integrating the Analytic Hierarchy Process (AHP) and the Fuzzy Comprehensive Evaluation Method, a risk assessment model is constructed to realize the quantitative characterization of risk levels and the accurate positioning of key management and control nodes. On this basis, from four dimensions of technological innovation, system improvement, management optimization, and emergency enhancement, an integrated "Early Warning-Prevention and Control-Disposal" prevention and control system is proposed, providing theoretical support and practical paths for the safety management of hazardous goods transportation by ships.

KEYWORDS

Hazardous Goods by Ships; Transportation Risks; Whole-Chain Management and Control; Risk Identification; Prevention and Control Measures

1. INTRODUCTION

1.1. Research Background and Significance

With the acceleration of global trade integration, the maritime transportation volume of hazardous goods has continued to rise. According to statistics from the International Maritime Organization (IMO), more than 1 billion tons of hazardous goods are transported by sea worldwide every year, involving more than 2,500 types, including explosives, chemicals, and radioactive substances. The safety of their transportation is directly related to the stability of the global shipping industry and the safety of the marine ecosystem. In recent years, accidents in the transportation of hazardous goods by ships have occurred frequently: in 2020, the collision between the "Sanchi" and the "Changfeng Crystal" resulted in crude oil leakage, causing large-scale marine pollution; in 2022, a container ship caught fire in the Red Sea due to improper stowage of hazardous goods, leading to the loss of ship control. Such accidents not only cause huge economic losses but also cause long-term damage to the marine ecosystem, highlighting the urgency of risk management and control in the transportation of hazardous goods by ships.

Currently, the transportation of hazardous goods by ships faces multiple challenges, such as the diversification of cargo types, the complexity of transportation environments, and the stricter regulatory requirements. Traditional risk management and control models mostly focus on a single link or isolated factors, lacking the ability of whole-chain and systematic risk identification and prevention, which makes it difficult to adapt to the safety management needs under the new situation. Therefore, from the perspective of the whole chain, systematically sorting out the risk points in each link of hazardous goods transportation by ships and constructing a scientific and efficient risk prevention and control system are of important theoretical value and practical significance for improving the transportation safety level, protecting the marine ecological environment, and promoting the high-quality development of the shipping industry.

1.2. Research Status at Home and Abroad

Foreign research on the risks of hazardous goods transportation by ships started early and has formed a relatively complete theoretical system and practical experience. In terms of risk identification, the International Maritime Dangerous Goods Code (IMDG Code) formulated by IMO clearly specifies the technical requirements for the classification, packaging, and stowage of hazardous goods, providing a standardized basis for risk identification [1]; Smith et al. (2018) identified the key risk factors in the transportation of liquefied natural gas (LNG) ships based on the Fault Tree Analysis (FTA) method, focusing on analyzing the coupling effect of equipment failures and human errors [2]. In the field of risk assessment, the Det Norske Veritas (DNV) developed a risk assessment system for the transportation of hazardous goods by ships, which realizes dynamic risk monitoring and early warning by combining big data technology; Johnson et al. (2021) used a Bayesian network model to quantify the collision risk of hazardous goods ships under extreme weather, providing technical support for route optimization [3].

Domestic research has developed rapidly in recent years, focusing on the localized practice of risk management and control. In terms of risk identification, Zhang Mingyuan et al. (2020) constructed a risk index system for the transportation of hazardous goods by ships from the four dimensions of "Man-Machine-Environment-Management", covering crew operations, ship equipment, navigation environment, and other aspects [4]; Li Na et al. (2021) identified prominent risk points such as concealment and misreporting in the consignment link for the transportation of containerized hazardous goods [5]. In terms of prevention and control measures, Wang Jianjun et al. (2022) proposed a traceability system for hazardous goods transportation based on blockchain technology, realizing the whole-process traceability of cargo information [6]; the Ministry of Transport has strengthened the dynamic supervision of ships transporting hazardous goods by establishing the "Ship Safety Supervision and Management System" [7].

Comprehensively, domestic and foreign research has achieved phased results, but there are still obvious shortcomings: first, risk identification is mostly limited to a single link, lacking a systematic sorting of the whole chain of "consignment-packing-navigation-unloading-emergency"; second, risk assessment models focus on technical factors, with insufficient consideration of the coupling effect of human and management factors; third, prevention and control measures are not targeted enough, making it difficult to adapt to the risk management and control needs of different transportation scenarios. Based on the perspective of whole-chain management and control, this paper makes up for the deficiencies of existing research and constructs a more complete risk identification and prevention system.

1.3. Research Content and Methods

The core research content of this paper includes three aspects: first, systematically identifying the core risk points in the whole chain of hazardous goods transportation by ships and constructing a multi-dimensional risk index system; second, establishing a scientific risk assessment model to realize the quantification of risk levels and the positioning of key management and control nodes; third, proposing targeted prevention and control measures from the four dimensions of technology, system, management, and emergency response.

The research adopts a combination of qualitative and quantitative methods: (1) Literature research method: systematically sorting out relevant domestic and foreign achievements, policies, and regulations to clarify the research foundation and cutting-edge directions; (2) Expert interview method: inviting safety directors of shipping enterprises, maritime supervision experts, port safety managers, and university scholars to identify whole-chain risk points and verify the rationality of indicators; (3) AHP-Fuzzy Comprehensive Evaluation Method: constructing a risk assessment model to realize level quantification; (4) Case analysis method: verifying the effectiveness of risk identification and prevention measures by combining typical accident cases.

2. WHOLE-CHAIN RISK IDENTIFICATION OF HAZARDOUS GOODS TRANSPORTATION BY SHIPS

The whole chain of hazardous goods transportation by ships covers five core links: consignment, packing, navigation, unloading, and emergency disposal. The risks in each link are interrelated, transmitted, and superimposed, forming a complex risk network. Based on the four-dimensional "Man-Machine-Environment-Management" analysis framework and combined with the operation characteristics of each link, this paper systematically identifies the whole-chain risk points and constructs a scientific risk index system.

2.1. Risks in the Consignment Link

As the source of transportation, the core risks in the consignment link lie in the distortion of cargo information and non-standard declaration: (1) Human factors: Consignors conceal or misreport the type of goods, or fail to truthfully provide key information such as hazardous characteristics and emergency disposal methods, leading to the loss of focus in subsequent management and control; (2) Management factors: Freight forwarding enterprises conduct a formal review of declaration materials and fail to implement the main responsibility of "who declares, who is responsible"; (3) Technical factors: The accuracy of hazardous goods classification and identification technology is insufficient, making it difficult to accurately determine the risk level, laying hidden dangers for subsequent transportation.

2.2. Risks in the Packing Link

The packing link directly determines the transportation stability of hazardous goods, and the risks are concentrated in operational standards and equipment support: (1) Human factors: Packing personnel have not received professional training, and there are illegal operations such as rough handling leading to packaging damage and mixed loading of goods with different properties; (2) Equipment factors: Loading equipment such as containers and pallets have quality defects, or do not conduct tightness testing and maintenance in accordance with specifications; (3) Management factors: There is a lack of effective supervision at the packing site, and the whole-process management and control of "pre-loading inspection, in-loading supervision, and post-loading confirmation" is not strictly implemented.

2.3. Risks in the Navigation Link

The navigation link is the stage with the most concentrated risks, affected by the coupling of multiple factors such as personnel, ships, and the environment: (1) Human factors: Crew members have weak safety awareness, and there are illegal operations such as fatigued driving and unauthorized route changes; insufficient emergency response capabilities make it difficult to deal with sudden dangers;

(2) Ship factors: Safety equipment such as fire-fighting and anti-pollution equipment is aging and ineffective, and the accuracy of navigation systems is insufficient; improper cargo stowage causes risks of displacement and capsizing; (3) Environmental factors: Extreme weather such as typhoons and huge waves, and complex sea conditions such as narrow waterways and reef areas increase navigation risks; the high density of navigation in port waters increases the collision risk; (4) Management factors: Shipping enterprises have incomplete safety management systems and fail to conduct regular training and drills; maritime supervision has blind spots in the dynamic management and control of the navigation process.

2.4. Risks in the Unloading Link

Risks in the unloading link stem from poor connection and non-standard operations: (1) Human factors: Insufficient communication between unloading personnel and crew members, failure to clarify the unloading sequence and safety precautions; illegal operations lead to cargo falling and leakage; (2) Equipment factors: Unloading equipment such as cranes and conveyors have unstable performance and are not specially adjusted according to the characteristics of the goods; (3) Environmental factors: The infrastructure such as ventilation and fire-fighting in the port loading and unloading area is incomplete, and the emergency response capability is weak; (4) Management factors: Port and shipping enterprises have not established a collaborative management mechanism, and the division of safety responsibilities in the unloading link is vague.

2.5. Risks in the Emergency Disposal Link

The emergency disposal link directly determines the effect of accident loss control, and the core risk is the insufficient emergency capability: (1) Human factors: Rescuers have insufficient professional literacy and are not proficient in the hazardous characteristics of goods and disposal procedures; (2) Equipment factors: The reserve of emergency materials such as chemical protective clothing and plugging equipment is insufficient or aging and ineffective; (3) Management factors: Emergency plans lack targeting and operability; the linkage mechanism between shipping enterprises, ports, maritime and other departments is incomplete, and the collaborative disposal capability is weak; (4) Environmental factors: The accident sea area is far from the shore-based, making it difficult for rescue forces to arrive quickly, extending the disposal window.

2.6. Construction of the Whole-Chain Risk Index System

Based on the above risk identification results and following the principles of scientificity, systematicness, and operability, a whole-chain risk index system for the transportation of hazardous goods by ships is constructed. The system is divided into the target layer (whole-chain risks of hazardous goods transportation by ships), the criterion layer (risks of five links), and the indicator layer (specific risk points). The specific content is shown in the following table:

Table 1. The Construction of the Whole-Chain Risk Index System

Target Layer	Criterion Layer	Indicator Layer
Whole-Chain Risks of Hazardous Goods Transportation by Ships	Risks in the Consignment Link	Risk of concealment and misreporting by consignors
		Risk of inadequate review by freight forwarders
		Risk of errors in cargo classification and identification
	Risks in the Packing Link	Risk of non-standard operations by packing personnel
		Risk of quality defects in loading equipment
		Risk of lack of supervision at the packing site
	Risks in the Navigation Link	Risk of illegal operations and insufficient emergency capabilities of crew members
		Risk of ship equipment failure and improper stowage
		Risk of extreme weather and complex sea conditions
		Risk of poor management of shipping enterprises and blind spots in maritime supervision
	Risks in the Unloading Link	Risk of improper operations and poor communication of unloading personnel
		Risk of unstable performance of unloading equipment
		Risk of incomplete port infrastructure and insufficient collaborative management
	Risks in the Emergency Disposal Link	Risk of insufficient professional literacy of emergency rescuers
		Risk of insufficient reserve and failure of emergency equipment
		Risk of incomplete emergency plans and unsound linkage mechanisms

3. CONSTRUCTION AND APPLICATION OF RISK ASSESSMENT MODEL FOR HAZARDOUS GOODS TRANSPORTATION BY SHIPS

3.1. Selection of Risk Assessment Methods

The risks of hazardous goods transportation by ships are characterized by fuzziness, uncertainty, and multi-factor coupling, and a single assessment method is difficult to accurately quantify the risk level. The Analytic Hierarchy Process (AHP) can decompose complex risk problems into a multi-level and multi-indicator system, and determine the weight of each indicator through expert judgment, solving the problem of indicator importance ranking; the Fuzzy Comprehensive Evaluation Method can effectively handle the fuzzy information in risk assessment and realize the quantitative evaluation of risk levels by constructing a fuzzy matrix. This paper combines the two methods to construct a risk assessment model of "weight determination-fuzzy evaluation-result analysis", improving the scientificity and accuracy of the assessment results [8].

3.2. Construction Steps of the Risk Assessment Model

3.2.1. Establishing a Hierarchical Structure

Based on the constructed whole-chain risk index system, the hierarchical relationship between the target layer (A), the criterion layer (B1-B5 corresponding to the risks of the five links), and the indicator layer (C1-C16 corresponding to specific risk points) is clarified, providing a clear analysis framework for subsequent assessment.

3.2.2. Determining Indicator Weights

Ten interdisciplinary experts (including 3 safety directors of shipping enterprises, 3 supervision experts from maritime administrations, 2 port safety managers, and 2 university scholars in shipping safety) were invited to compare the indicators of each layer pairwise using the 1-9 scaling method to construct a judgment matrix. After verifying the rationality of the matrix through consistency test (CR<0.1), the eigenvalue method was used to calculate the indicator weights. The weight results of the criterion layer show that the risk weight of the navigation link is the highest (0.35), followed by the emergency disposal link (0.25), the consignment link (0.18), the packing link (0.12), and the unloading link (0.10), indicating that navigation and emergency disposal are the core management and control links.

3.2.3. Constructing the Fuzzy Comprehensive Evaluation Matrix

The risk levels are divided into five gradients: "Extremely High Risk (V1), High Risk (V2), Medium Risk (V3), Low Risk (V4), and Extremely Low Risk (V5)". Experts are organized to conduct fuzzy evaluation on the risk points of each indicator layer, determine the membership degree of each indicator to different risk levels, and construct the fuzzy evaluation matrix R.

3.2.4. Calculating the Comprehensive Evaluation Result

Using the weighted average synthesis method, the indicator weight vector W is calculated with the fuzzy evaluation matrix R to obtain the comprehensive evaluation result vector $B=W\times R$. According to the maximum membership degree principle, the risk level of the whole chain of hazardous goods transportation by ships is determined.

3.3. Case Analysis of Model Application

Taking the hazardous goods transportation business of a shipping enterprise on the "Dalian-Singapore" route as an empirical object, the constructed model is applied to conduct risk assessment. This route mainly engages in the transportation of liquefied petroleum gas (LPG), using a 15,000-ton LPG special transport ship, with a one-way navigation cycle of about 7 days.

Through expert evaluation and data collection, the indicator weights are determined and the fuzzy evaluation matrix is constructed. The comprehensive assessment results show that the transportation risk level of this route is "Medium Risk". Among them, the indicators such as "insufficient emergency capabilities of crew members" and "extreme weather risk" in the navigation link, and "unsound emergency linkage mechanism" in the emergency disposal link have prominent membership degrees in high risk, which are the core management and control points. In response to the assessment results, the enterprise implemented special emergency training for crew members, optimized the route to avoid typhoon-prone areas, and established an emergency linkage mechanism with port and shipping as well as maritime departments along the route. The subsequent re-assessment showed that the risk level was reduced to "Low Risk", verifying the effectiveness and practicality of the model.

4. CONSTRUCTION OF RISK PREVENTION AND CONTROL MEASURE SYSTEM FOR HAZARDOUS GOODS TRANSPORTATION BY SHIPS

Based on the results of whole-chain risk identification and assessment, and combined with the concept of "Early Warning-Prevention and Control-Disposal" integration, a risk prevention and control system for the transportation of hazardous goods by ships is constructed from four dimensions of technological innovation, system improvement, management optimization, and emergency enhancement, realizing the whole-process and multi-dimensional closed-loop management and control of risks.

4.1. Technological Innovation: Constructing an Intelligent Risk Early Warning and Traceability System

4.1.1. Promoting Intelligent Identification and Detection Technology for Hazardous Goods

Develop rapid identification equipment for hazardous goods based on spectral analysis and artificial intelligence to realize accurate classification of consigned goods and detection of hazardous characteristics, curbing the concealment and misreporting of goods from the source. Promote CT scanning and intelligent image recognition technology in the port container inspection link to automatically verify the consistency between the goods inside the container and the declared information, improving the inspection efficiency and accuracy.

4.1.2. Establishing an Intelligent Ship Navigation Monitoring System

Integrate resources such as the Automatic Identification System (AIS), Global Positioning System (GPS), and meteorological navigation system to build an intelligent ship navigation monitoring platform. By collecting real-time data on ship position, navigation status, equipment parameters, and sea condition meteorology, big data analysis technology is used to realize navigation risk prediction, automatically warn of abnormal situations such as illegal operations by crew members and equipment failures, and provide data support for route optimization and safety decision-making.

4.1.3. Applying Blockchain Technology to Realize

Whole-Chain TraceabilityConstruct a blockchain-based traceability system for the transportation of hazardous goods by ships, uploading whole-chain data such as cargo consignment information, packing records, navigation data, unloading information, and emergency disposal status to the chain to achieve tamper-proof, full-process traceable, and shared data. Subjects such as shipping enterprises, ports, maritime authorities, and consignors obtain corresponding data through permission management, strengthening the collaborative supervision of each link and solving the problem of information asymmetry.

4.2. System Improvement: Improving Whole-Chain Safety Supervision Laws and Regulations

4.2.1. Improving the Declaration System for Hazardous Goods Transportation

Revise the Regulations on the Safety Supervision of Ships Carrying Hazardous Goods, clarify the main responsibilities of consignors and freight forwarding enterprises, increase the penalty for concealing or misreporting hazardous goods, and establish an industry "blacklist" system [7]. Promote the electronic declaration model for hazardous goods to standardize and formalize declaration information, improving the efficiency and convenience of declaration and supervision.

4.2.2. Standardizing Operation Standards for Packing and Unloading

Formulate the Safety Operation Specifications for the Packing and Unloading of Hazardous Goods by Ships, clarifying the qualification requirements and operation procedures for packing and unloading personnel, and specifying the quality standards and inspection cycles of loading equipment. Require port and shipping enterprises to establish on-site supervision mechanisms for packing and unloading, and retain complete operation records for traceability and verification.

4.2.3. Establishing an Inter-Departmental Collaborative Supervision System

Establish a collaborative supervision mechanism among multiple departments including the Ministry of Transport, Maritime Safety Administration, Ministry of Emergency Management, and Ministry of Ecology and Environment, clarifying the responsibility boundaries of each department in the supervision of hazardous goods transportation, and realizing the sharing of supervision information and joint law enforcement. Conduct regular joint law enforcement inspections, focusing on investigating potential risks in core links such as consignment, navigation, and emergency response.

4.3. Management Optimization: Strengthening Enterprise Main Responsibility and Personnel Management

4.3.1. Improving the Safety Management System of Shipping Enterprises

Shipping enterprises should establish a safety management system featuring "full-staff participation and whole-process control", formulate safety management systems, operating procedures, and emergency plans for the transportation of hazardous goods. Conduct regular safety risk assessments and establish a closed-loop rectification mechanism for problems identified in the assessments. Increase safety investment to ensure the funding needs for ship equipment renewal, safety training, and emergency material reserves.

4.3.2. Strengthening Professional Training and Assessment of Employees

Establish a hierarchical training system for employees, carrying out targeted safety training for different positions such as consignment, packing, crew, unloading, and emergency rescue, focusing on improving the ability of hazardous goods identification, standardized operation, and emergency disposal. Implement an employee qualification certification system, organize regular assessments, and prohibit those who fail the assessments from taking up their posts.

4.3.3. Implementing a Safety Performance Incentive and Accountability Mechanism

Shipping enterprises should establish a safety performance incentive mechanism, directly linking safety management effectiveness with employees' salaries and promotions to stimulate the enthusiasm of all staff for safety management. At the same time, establish a strict safety accountability mechanism, and investigate the responsibility of responsible personnel who violate safety systems and cause safety accidents in accordance with laws and regulations.

4.4. Emergency Enhancement: Constructing a Whole-Chain Emergency Linkage System

4.4.1. Improving the Emergency Rescue Plan System

Formulate differentiated emergency rescue plans according to the characteristics of different types of hazardous goods and transportation scenarios, clarifying the emergency organization structure, response procedures, and disposal measures. Organize regular inter-departmental emergency drills to test the operability of the plans and improve the collaborative combat capability of the rescue team.

4.4.2. Strengthening the Construction of Emergency Rescue Equipment and Forces

Increase investment in emergency rescue equipment, reserve sufficient emergency materials such as chemical protective clothing, plugging equipment, fire-fighting equipment, and oil dispersants on ships, ports, and coastal shore-based facilities, and establish a regular maintenance and update mechanism. Establish a professional emergency rescue team for hazardous goods, equipped with helicopters, emergency rescue ships, and other equipment to improve the emergency response speed.

4.4.3. Establishing an Inter-Regional Emergency Linkage Mechanism

Strengthen emergency linkage between domestic ports and maritime departments, build an emergency resource sharing platform, and realize the rapid deployment of rescue forces. Actively participate in international maritime emergency cooperation, and establish an emergency linkage mechanism for the transportation of hazardous goods with countries along the "Belt and Road" to collaboratively respond to cross-border transportation accidents.

5. CONCLUSIONS AND PROSPECTS

5.1. Research Conclusions

Based on the perspective of whole-chain management and control, this paper systematically conducts research on risk identification and prevention and control measures for the transportation of hazardous goods by ships. The main conclusions are as follows: (1) There are 16 core risk points in the whole chain of hazardous goods transportation by ships, distributed in five links: consignment, packing, navigation, unloading, and emergency disposal. Among them, the navigation link and emergency disposal link have the highest risk weights, which are the key points of risk management and control; (2) The constructed AHP-Fuzzy Comprehensive Evaluation Model can effectively quantify the risk level of hazardous goods transportation by ships [8], clarify key management and control nodes, and the case application verifies the effectiveness of the model; (3) The risk prevention and control system constructed from four dimensions of technological innovation, system improvement, management optimization, and emergency enhancement realizes the integrated "Early Warning-Prevention and Control-Disposal" management and control of risks, providing a scientific plan for the safety management of hazardous goods transportation by ships.

5.2. Research Prospects

Future research can be deepened from three aspects: (1) In the field of risk assessment, combine the Internet of Things and big data technology to construct a dynamic assessment model to realize real-time risk monitoring and dynamic update; (2) At the technical application level, explore the application of cutting-edge technologies such as artificial intelligence and digital twins in risk management and control to improve the intelligence level of management and control; (3) From the perspective of international cooperation, study the establishment of unified international risk management and control standards and emergency linkage mechanisms for cross-border transportation risks, contributing Chinese wisdom to global shipping safety.

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