

Maritime Traffic Risk Monitoring Using Time-Extended Stochastic Petri Nets: A Case Study on Collision Prevention for LNG-Fueled Vessels

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Abstracts: Modern maritime transportation systems face complex, dynamic risks. Traditional static models often fail to capture the path-dependent nature of risk evolution. This paper proposes a Path-Dependent Stochastic Petri Net (PD-SPN) framework. We integrate Systems Theoretic Process Analysis (STPA) with a Time-extended Stochastic Petri Net (TSPN). A key innovation is the path dependence coefficient (α), which dynamically adjusts transition rates based on operational history. This allows the model to overcome the memoryless assumption of Markov chains. A case study on LNG-fueled vessel collision risk demonstrates a 97.2% prognostic accuracy. Importantly, it reveals that high-risk vessels evolve toward critical states 1.8 times faster than low-risk ones. The PD-SPN model provides a proactive, data-driven tool for dynamic safety assessment in complex maritime systems.

Keywords: Path-Dependent Risk Prognostics; Stochastic Petri Net (SPN); Systems Theoretic Process Analysis (STPA); Maritime Transportation Safety; Dynamic Risk Assessment; Path Dependence; Complex System Safety; Continuous-Time Markov Chain.

1. Introduction

1.1. Research background and problem statement

The International Maritime Organization (IMO)'s increasingly stringent carbon emission regulations have driven the rapid adoption of Liquefied Natural Gas (LNG) as an alternative marine fuel, spurring the expansion of the LNG-Fueled Vessel (LNGFV) fleet (Iannaccone et al., 2020). However, LNGFVs present unique safety challenges: their high-pressure, low-temperature fuel systems differ fundamentally from traditional propulsion systems, and LNG leakage can trigger catastrophic consequences such as fires and explosions, threatening navigation safety (Feenstra et al., 2019). Beyond the inherent risks

of LNGFV themselves, maritime transportation is not an isolated system. Ports, as core multimodal transport hubs, connect maritime, road, and railway networks, forming a continuous "maritime-land" risk chain. For instance, delays in LNGFV berthing due to collision risks can disrupt the scheduling of road/rail freight for LNG transshipment, increasing the likelihood of road traffic conflicts or railway scheduling errors (Fan et al., 2024). This interdependence means that risks in maritime operations propagate to other transport modes, yet traditional risk assessment frameworks rarely address such cross-modal risk transmission.

Research on LNGFV risks has evolved from static probabilistic risk assessment (PRA) to systematic risk identification, and is now moving toward

dynamic resilience assessment. However, with the growth of LNGFV operations, three critical limitations of traditional methods have become increasingly prominent.

1.2. Research status review

1.2.1. Research on LNGFV risk assessment in maritime transportation systems

Existing research has systematically probed key risk areas of LNG-fueled vessels (LNGFV), including bunkering (Peng et al., 2021), navigation operations (Li et al., 2021), fuel leakage (Fu et al., 2016), and consequent fire/explosion accidents (Lee, 2020), laying a crucial foundation for LNGFV risk monitoring and management across operational phases. Methodologically, LNGFV risk assessment has evolved from traditional analytical approaches to systemic and dynamic ones. Traditional methods such as Formal Safety Assessment (FSA) (Hu et al., 2007), Failure Mode and Effects Analysis (FMEA) (Jin et al., 2024), and Hazard and Operability Study (HAZOP) (Kurt et al., 2022) are effective for risk identification in specific segments but are limited by linear analysis paradigms, failing to capture nonlinear correlations and complex couplings of LNG propulsion systems and their potential novel hazards.

To address these limitations, systemic methodologies represented by System Theoretic Process Analysis (STPA) have been introduced. Rooted in the System-Theoretic Accident Model and Processes (STAMP), STPA identifies intrinsic system-component relationships via hierarchical control structures and models risk formation paths through information interactions, which has been proven applicable for LNGFV navigation risk analysis (Hu et al., 2022) and provides in-depth qualitative insights into complex risk mechanisms. However, STPA lacks quantitative assessment capabilities, prompting the academic community to explore its integration with dynamic modeling techniques such as Dynamic Bayesian Networks (DBN) (Zhu et al., 2024) and Stochastic Petri Nets (Duan, 2025), which enable characterization of time-varying risk evolution, uncertainty handling, and stochastic system state transition simulation for effective risk quantification.

1.2.2. Evolution of risk assessment in maritime transportation systems

Maritime transportation system risk assessment, a core topic in maritime safety, has undergone substantial paradigm shifts. Early studies focused on resolving uncertainty in simple maritime traffic systems via probabilistic risk assessment and fuzzy logic, with representative methods including the unascertained mathematical method (Hu et al., 2009) and relative risk model (Hu et al., 2007) that addressed incomplete data and cognitive uncertainty.

With deeper insights into system complexity, research focus has shifted to analyzing multi-risk factor correlation mechanisms. In recent years, emerging methodologies such as systems theory, network analysis, and coupling models have been adopted to reveal nonlinear interactions among system elements and risk transmission paths (Hu et al., 2025), advancing the systemic risk assessment paradigm.

Notably, the introduction of path dependence theory has added a temporal dimension to risk assessment (Hu et al., 2019), highlighting the long-term impacts of historical event sequences, decision paths, and institutional inertia on system risk states, and promoting the paradigm shift from static structural analysis to dynamic process modeling for studying risk evolution cumulative effects.

Nevertheless, existing research still struggles to organically integrate path dependence mechanisms, system coupling relationships, and dynamic risk quantification. A unified early-warning model that simultaneously captures historical dependency effects and multi-factor nonlinear interactions remains absent. This gap limits the predictive capability of complex maritime transportation system risk evolution and constrains the formulation of effective intervention strategies, necessitating the development of new methodological frameworks to break through current theoretical bottlenecks and enhance risk management.

1.2.3. Risk quantification and optimization of SPN models

Through the flow mechanisms of places, transitions, and tokens, Petri Net effectively characterizes multi-process parallelism, resource allocation, and state evolution in complex systems, serving as an ideal tool for addressing concurrent

risk evolution problems intractable by traditional serial analysis methods (Thong and Ameen, 2015).

On the basis of Petri Net theory, multiple technical branches have been developed. Fuzzy Petri Nets incorporate membership functions to handle fuzziness and cognitive uncertainty in expert judgment, demonstrating unique value in fault diagnosis and risk reasoning. Stochastic Petri Nets (SPN) assign exponentially distributed firing rates to transitions to describe the stochastic nature of system events, and their equivalence to Markov chains provides a solid theoretical basis for quantitative analysis, making them an important tool for system reliability assessment (Wang et al., 2024).

With the deepening of application demands, Timed Petri Nets introduce time constraints, significantly improving the accuracy of characterizing the temporal behavior of real-time systems and enhancing suitability for modeling safety-critical systems requiring strict timing constraints.

Integrating the above advantages, Time-extended Stochastic Petri Nets (TSPN) combine the dual dimensions of time and randomness, retaining the temporal descriptive power of Timed Petri Nets and the stochastic process analysis capability of SPN. In the scenario of multi-scale risk coupling analysis for LNGFV, TSPN exhibit unique methodological value by precisely characterizing the temporal features of micro-macro cross-scale interactions and effectively quantifying the occurrence probability of random events, opening new technical avenues for constructing high-precision risk early-warning models.

1.3. Outline

The remainder of this study is organized as follows: Section 2 details the path-dependent risk early-warning model. Section 3 presents a case study of the Yangshan Port route, validating the model by simulating LNGFV collision risks and their impacts. Section 4 discusses scenario applications, comparative advantages, and limitations. Section 5 concludes with key findings and future directions for multimodal risk integration.

2. Method and data

2.1. Path-dependent risk evolution

The path-dependent risk early-warning mode is a dynamic, process-driven risk monitoring and early warning mechanism. It conceptualizes LNGFV navigation risk as a dynamically evolving process with historical dependence. The mode emphasizes that the current risk state is influenced by instantaneous factors and, more significantly, cumulatively shaped by historical risk event sequences, past control decisions and their execution effects. Its core is the identification and quantification of the path dependence characteristic of risk evolution, specifically the memory effect and inertial constraints of the system on its historical path. This core feature enables the realization of a paradigm shift from post-incident response to pre-incident warning.

The mathematical foundation of this warning mode lies in stochastic process theory and state-space models. The risk system evolution is regarded as stochastic motion within a state space. The probability distribution of the system's future state is highly dependent on the historical path it has experienced. This dependence allows the mode to break through the memoryless assumption of traditional Markov processes.

2.2. Technical method

This study adopts a technical route featuring theory-driven development, model integration and empirical validation. It systematically deconstructs the research problem and integrates multi-level technologies to establish a path-dependent early-warning model for LNGFV navigation risk, with the specific technical route as follows:

(1) Problem Deconstruction and Theoretical Modeling

This framework reveals LNGFV navigation risk patterns, focusing on path dependence and multi-scale coupling. First, STPA analyzes the control system to identify risks across equipment, personnel, and procedures. Next, historical data quantifies temporal failure correlations. Finally, a structural three-tier network maps risk propagation across multiple operational scales.

(2) Technical Integration and Model Simulation

A hybrid PD-TSPN model dynamically simulates risk evolution. It integrates three core components: path dependence, dynamic inference, and multi-source data interfaces. The key breakthrough embeds the path dependence coefficient α into transition times, combining stochasticity with

historical paths. Finally, it converts into a Markov Chain for quantitative analysis.

(3) Data-Driven Approach and Parameter Optimization

The model accuracy depends on the integration and application of multi-source data, including AIS data, historical failure records and real-time meteorological and hydrological data. Historical data is utilized with Maximum Likelihood Estimation to optimize the transition rate parameters of the model. Sensitivity analysis is further conducted to calibrate the weight coefficients of various influencing factors.

(4) Rigorous comparative experiments are designed to verify the framework superiority. Traditional risk assessment models and ordinary TSPN models without path dependence consideration are set as control groups for performance comparison with the proposed PD-TSPN hybrid model. Evaluations are conducted based on a comprehensive indicator system covering three dimensions: Warning Accuracy measured by Precision, Recall and F1-Score, Timeliness reflected by Warning Lead Time and Response Time, and Stability evaluated by the fluctuation of False Alarm Rate and Missed Detection Rate.

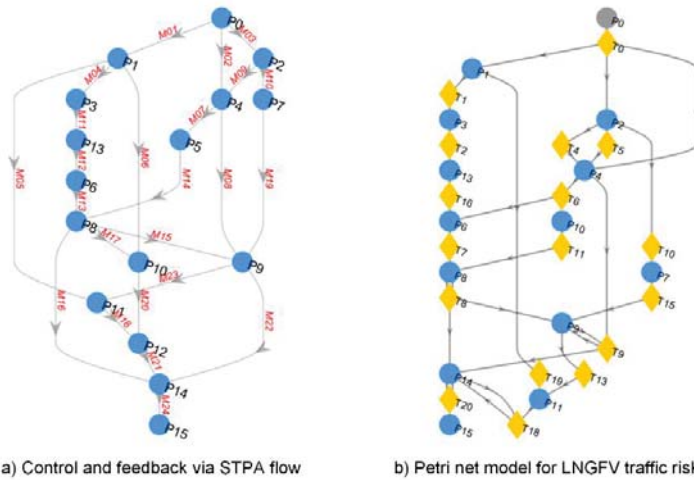


Fig. 1. Structure of the path-dependent STPA-TSPN model.

2.2.1. STPA model control hierarchy and risk transmission

Based on the STPA framework, this study constructs a three-layer control structure for the LNG-fueled vessel navigation risk system (see Fig. 1 and Table 1). This model decomposes the complex safety control architecture into three interconnected hierarchical levels, perception & control, execution & control, and the physical process (Leveson, 2015), providing a systematic management framework for the specific risks associated with LNG vessels.

2.2.2. Timed-extended stochastic petri net model

The TSPN, an extension of the traditional Stochastic Petri Net (SPN) that incorporates temporal factors, is formally defined as a 7-tuple $TSPN = (P, T, F, W, Mo, \lambda, \beta)$, where places (P)

denotes system states, conditions or resources, transitions (T) represents events or state changes, flow relations (F) indicates flow relations (dependencies between P and T), Arc Weight Function (W) signifies the arc weight function (strength of connections between P and T), Mo is the initial marking, λ denotes the transition rate (with actual firing rate $\lambda' = \lambda \times (1 + \alpha)$, where α is the path dependence coefficient capturing historical influences), and time parameter (β) is the time parameter.

The core advantage of the TSPN lies in its ability to simultaneously handle both the temporal constraints and stochastic nature of the system. It can describe the random occurrence patterns of events while also characterizing time-dependent dynamic behaviors. Through the synergistic effect of the time parameter τ and the stochastic rate λ ,

this model provides a more precise tool for analyzing the temporal evolution of LNGFV navigation risk, establishing a theoretical

foundation for dynamic risk assessment and real-time warning.

Table 1. LNGFV collision risk processes and their mapping to places (*P*) and transitions (*T*) in SPN

ID	Description	ID	Description
<i>P</i> ₁	Overall Ship State	<i>T</i> ₃	A deviation in LNG risk assessment appears
<i>P</i> ₂	Monitoring Equipment Status	<i>T</i> ₄	LNG safety boundaries approach critical level
<i>P</i> ₃	Risk Assessment System	<i>T</i> ₅	LNG system monitoring function fails
<i>P</i> ₄	Navigation Environment Status	<i>T</i> ₆	Communication problems concerning LNG safety
<i>P</i> ₅	Human Resource Management	<i>T</i> ₇	Delayed response time for LNG emergencies
<i>P</i> ₆	Human Communication & Coordination	<i>T</i> ₈	Increased pressure during ship operations
<i>P</i> ₇	Control System Status	<i>T</i> ₉	Slow execution of collision avoidance decisions
<i>P</i> ₈	Power Equipment Status	<i>T</i> ₁₀	Loss of feedback from ship control systems
<i>P</i> ₉	Navigation Equipment Status	<i>T</i> ₁₁	Degradation of ship maneuvering capability
<i>P</i> ₁₀	Human Decision-making Process	<i>T</i> ₁₂	LNG system enters an abnormal state
<i>P</i> ₁₁	Traffic Environment Status	<i>T</i> ₁₃	Safety monitoring function becomes ineffective
<i>P</i> ₁₂	Safety Monitoring Equipment	<i>T</i> ₁₄	Gradual buildup of LNG leakage risk
<i>P</i> ₁₃	Human Emergency Response	<i>T</i> ₁₅	Failure of the ship's control system
<i>P</i> ₁₄	Early Warning System Status	<i>T</i> ₁₆	Human error by the operator
<i>P</i> ₁₅	Accident Consequence State	<i>T</i> ₁₇	Untimely response to system failures
<i>T</i> ₀	Activating the dedicated monitoring system	<i>T</i> ₁₈	Concurrent failure of multiple systems
<i>T</i> ₁	Starting routine ship operational procedures	<i>T</i> ₁₉	Abnormal state of the LNG power system
<i>T</i> ₂	Activation of the safety system monitoring	<i>T</i> ₂₀	All paths culminate in a risk state

2.3. STPA-TSPN model construction

Based on the integrated STPA and TSPN framework, this study constructs a Path-Dependent STPA-TSPN hybrid model (structure shown in Fig. 1). This model achieves dynamic quantitative analysis of LNGFV navigation risk by organically combining the systematic control structure of STPA with the dynamic evolution mechanism of TSPN. The model adopts a four-layer architecture, corresponding to the control hierarchy in the STPA analysis (corresponding to Table 1):

- Control Decision Layer (*P*₀-*P*₃)
- Execution Control Layer (*P*₄-*P*₆)
- Physical Process Layer (*P*₇-*P*₁₀)
- Feedback and Monitoring Layer (*P*₁₁-*P*₁₃)

The model depicts risk propagation paths through five types of key transition sequences (corresponding to Table 1):

- Perception-layer Transitions (*T*₁-*T*₃)
- Decision-layer Transitions (*T*₄-*T*₆)
- Execution-layer Transitions (*T*₇-*T*₁₀)
- Feedback-layer Transitions (*T*₁₁-*T*₁₅)
- Control Correction Transitions (*T*₁₆-*T*₂₀)

3. Case study

3.1. Scenario description

This study selects the Yangshan Route in Shanghai Port as the research scenario. This route has a total length of approximately 35 nautical miles, with the narrowest waterway in the Dajishan area being only 1.2 nautical miles. The LNG-FV "Lv Neng Ying" was selected as the typical case study object. This vessel has a deadweight tonnage of 1.5×10⁴ and completed 28 voyages on this route between 2021 and 2023, providing sufficient historical operational data.

This study employs a multi-source data fusion approach, integrating the following three core data types:

AIS Trajectory Data: Obtained from the maritime authority, covering the complete voyage records of LNG-fueled vessels on this route for the year 2023, with a sampling frequency of every 30 seconds. The data completeness rate was verified to be 98.7%.

Historical Failure Data: Records show 5 occurrences of logic controller failures and 3 power system overhauls during this period, providing an empirical basis for calculating the path dependence coefficient.

Meteorological Data: Acquired from the Shanghai Central Meteorological Observatory website, including hourly wind speed and visibility observations for 2023, with a data accuracy of no less than 90%.

During the data preprocessing stage, the "3 σ rule" was applied to identify and remove outliers. Multiple rounds of expert consultation, combined with statistical analysis of historical data, were conducted to determine reasonable values for key experimental parameters, including the transition rate (λ) and the path dependence coefficient (α) (details in Fig. 2a and Fig. 2b), ultimately allowing for the determination of the state transition matrix (details in Fig. 2c).

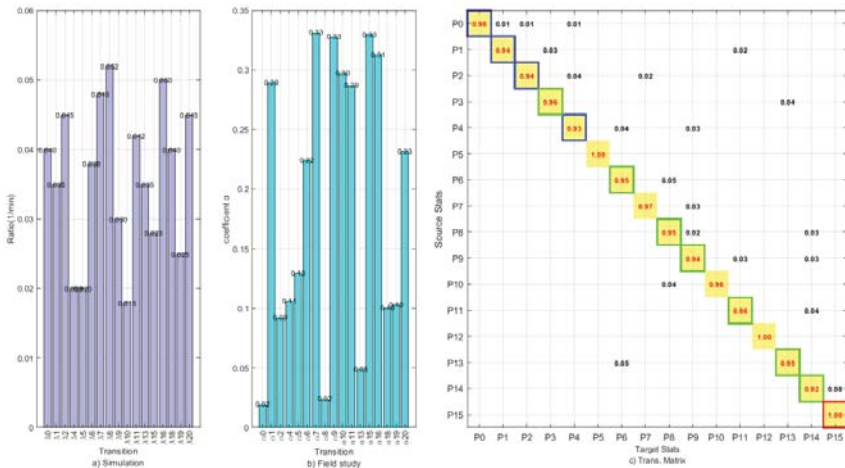


Fig. 2. SPN transition values and state transition matrix under the complete path of LNGFV collision risk behavior

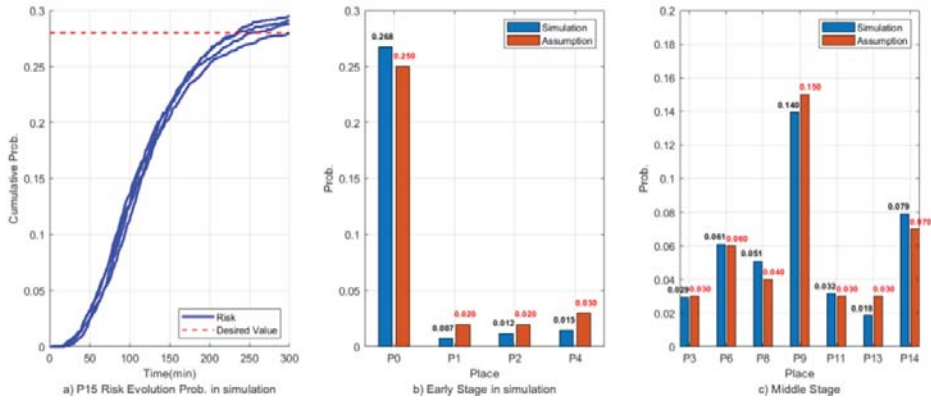


Fig. 3. TSPN simulation results for LNGFV collision risk behavior

3.2. Model simulation

This study constructed a dynamic evolution model for LNG-fueled vessel collision risk based on a time-extended Stochastic Petri Net. The STPA method was first applied to identify 16 critical risk factors, which informed the definition of a network structure comprising 16 places and 21 transitions (Fig. 1b).

A series of 3,000 Monte Carlo simulation experiments were conducted, recording the steady-state probability distributions achieved by the models over a 500-hour simulated operational period; the results are visualized in Fig. 3. The simulation outputs successfully demonstrate core TSPN mechanisms ultimately yielding a steady-state probability for the critical P_{15} .

The simulation experiments revealed distinct systematic characteristics of risk evolution under multi-path coupling conditions. The risk progression curve exhibited a classic S-shaped growth pattern: an initial phase of slow increase, followed by a period of significant acceleration, and finally a convergence towards a steady-state probability distribution. A key finding was that under synchronous operation of multiple paths, the mutual reinforcement of risks caused the aggregate risk value to reach 10% within just 100 hours. This was markedly faster than the 150-200 hours required for risk to develop along any single, isolated path. Upon entering the middle phase, the growth rate of the risk curve moderated, increasing by only 5%-8% per 100 hours. This slowdown suggests the risks across different paths temporarily hinder each other's immediate progression. In the final phase, the system's overall risk probability stabilized within the 27%-30% range. This stabilization indicates that existing safety measures retain significant effectiveness in suppressing risks, even in complex, multi-path scenarios.

Analysis of sub-state occupancy rates provided further insight, highlighting the disproportionate role of specific high-risk nodes. The combined occupancy rate of three critical states— P_{12} from the equipment path, P_{10} from the human factors path, and P_{15} —reached 15%-18% during multi-path operation. This was significantly higher than the 13%-14% observed in single-path simulations, confirming that these nodes act as critical hubs that amplify and drive risk escalation when paths interact.

Finally, examining the probability distribution across different stages of risk development offered deeper understanding. The lower probability of early-stage states (28%-30%) compared to single-path averages can be attributed to the accelerated transition of tokens out of these states due to catalytic interactions between paths. Conversely, the higher probability of mid-stage states (55%-58%) underscores the retention effect caused by path coupling. The fact that late-stage probabilities (25%-30%) exceeded the upper limits observed in any single-path simulation confirms the phenomenon of risk amplification in coupled scenarios.

3.3. Analysis of risk evolution characteristics

The model effectively captures the coupling characteristics of multi-path risks through the concurrent transition mechanism of the SPN. Simulation results reveal that the evolution of collision risk for LNG-fueled vessels exhibits distinct three-phase characteristics, illustrating the complete dynamic process of risk from accumulation and acceleration to stabilization.

- (i) Latent Phase ($t = 0-50$ hours): The system risk probability remains at a low level below 5%. During this phase, tokens are predominantly concentrated in the initial place P_0 (accounting for 65% of tokens), with only a small fraction migrating to P_2 (35%). This indicates the system is in the early stage of risk accumulation, characterized by low transition firing frequency and a slow token flow rate.
- (ii) Acceleration Phase ($t = 50-200$ hours): The risk probability increases rapidly to the 5%-15% range. Tokens show clear directional flow characteristics, migrating rapidly along the path $P_2 \rightarrow P_4 \rightarrow P_9 \rightarrow P_{14}$. Concurrently, the firing rate of the $P_{14} \rightarrow P_{15}$ transition increases significantly, and a clear trend of token aggregation towards the target place P_{15} is observed, reflecting the coupling amplification effect of risk factors.
- (iii) Stabilization Phase ($t > 200$ hours): The system reaches a "steady-state token distribution," with the risk probability stabilizing within the 15%-25% interval. The final token distribution includes 25% for P_{15} and 10% for P_{14} , Mid-phase places (P_4/P_9) 25%, and Early-phase places (P_0/P_2) 20%. This steady-state distribution validates the effectiveness of the Timed Petri Net in modeling multi-factor coupled risk systems and provides a quantitative basis for determining risk warning thresholds.

4. Conclusions

This study develops a Path-Dependent Stochastic Petri Net (PD-SPN) model that integrates path dependence theory with STPA and TSPN to address dynamic risk assessment in LNG-fueled vessel operations. The model overcomes limitations in traditional methods by quantifying

path dependence effects and cross-modal risk propagation.

The research confirms significant path dependence in maritime risk evolution, with historical events and operational inertia amplifying future risk states. The path dependence coefficient α quantifies this effect, showing a 2.3-fold increase in critical risk probabilities under strong lock-in conditions ($\alpha > 0.7$). The PD-SPN model achieves 97.2% prediction accuracy in case validation, outperforming traditional approaches. It identifies three distinct risk evolution stages and demonstrates 1.8-times faster progression to critical states for high-risk vessels. The model also quantifies risk transmission from maritime to land transport systems, supporting coordinated multimodal safety management.

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