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Safety Risk Assessment of Hydrogen-Powered Ships Using FMEA and Multi-Expert Evaluation

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ABSTRACT

This paper explores the critical safety challenges posed by the adoption of hydrogen as a marine fuel. The study applies an integrated risk assessment framework that combines failure mode and effects analysis (FMEA), hazard identification (HAZID), and a survey of 49 maritime experts. Key risks identified include hydrogen leakage, storage system rupture, and inadequate crew training. The findings indicate a strong consensus among experts regarding the urgent need to address tank integrity, sensor reliability, and operational preparedness. Recommendations emphasize the development of hydrogen-specific training, implementation of real-time monitoring, and updating international regulatory codes. This work contributes to improving hydrogen safety management and supports the transition toward sustainable maritime operations.

Keywords- Expert survey, FMEA, HAZID, Hydrogen fuel, Maritime safety

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I. INTRODUCTION

The maritime sector is shifting toward clean energy sources in response to international pressure for emissions reduction. Hydrogen is a strong candidate due to its zero-emission profile during combustion. However, its safe integration requires thorough analysis of the physical and operational hazards associated with storage, transfer, and utilization onboard ships. This paper presents a structured evaluation of these risks and proposes mitigation strategies based on expert insights.

II. Literature review

The body of literature on hydrogen as a maritime fuel remains comparatively limited but has expanded in recent years. Studies by [1] and [2] have underscored both the environmental benefits and the safety concerns tied to hydrogen adoption. In addition, international organizations such as the IMO have begun to explore hydrogen within the framework of alternative fuels, although dedicated standards remain under development. A key theme in recent work is the lack of harmonized global safety codes, which creates operational uncertainty and hinders investment in hydrogen-powered vessels. Bayesian network approaches [3] and safety barrier analyses [4] represent methodological advances, yet there remains a gap in integrating these quantitative methods with qualitative expert input. This paper addresses that gap by combining structured risk modeling with perception-based surveys, providing a more holistic perspective.

Literature indicates hydrogen's potential for maritime use, yet there are substantial gaps in the safety framework. The outlined alternative fuel risks. It emphasized safety procedures, while the IMO has begun outlining protocols for hydrogen usage. Nonetheless, research combining structured risk assessment with real-world expert perception is scarce.

Several recent studies have investigated hydrogen safety in maritime contexts from different perspectives.
Jeong et al. [29] conducted a comparative risk assessment of gaseous and liquid hydrogen fuel supply systems, highlighting distinct risk profiles in explosion and leakage behavior. Similarly, **Kang et**

al. [32] employed a Bayesian network with bidirectional reasoning to analyze hydrogen leakage risks in fuel-cell ships, underscoring the necessity of probabilistic approaches to capture uncertainty.

Furthermore, systematic reviews such as **Koromila et al. [31]** stress that most existing studies focus heavily on technical failure modes while underrepresenting organizational and regulatory dimensions.

Building on these insights, the present research advances the field by explicitly incorporating expert perceptions through surveys combined with conventional FMEA-based gap analysis. This integrated approach not only identifies technical vulnerabilities but also highlights systemic gaps, providing a more comprehensive basis for maritime hydrogen safety management.

III. Methodology

3.1 Survey Design and Participants

To complement the FMEA-based gap analysis, an expert survey was conducted. A total of **49 experts** participated, representing diverse professional backgrounds, including ship operation (captains and officers), shipbuilding engineers, safety and risk management specialists, academic researchers, and regulatory officials.

The survey was structured into three main components:

1. **Quantitative assessment of failure modes** using the FMEA Risk Priority Number (RPN).
2. **Evaluation of concern levels** for key safety domains, such as tank integrity, crew training, monitoring systems, and emergency response.
3. **Open-ended questions** that allowed respondents to provide additional insights on emerging risks, including bunkering operations, regulatory uncertainty, sensor reliability, and training gaps.

This design enabled the integration of **quantitative scoring and qualitative insights**, addressing potential gaps in conventional risk assessment methods.

Field/Profession	Number of Respondents	Percentage (%)
Ship Operation Experts (Captains, Officers)	15	30%
Shipbuilding Engineers	12	24%
Safety & Risk Management Experts	10	20%
Academics/Researchers	7	14%
Regulators/Policy Makers	5	10%
Total	49	100%

Table 1. Composition of survey respondents

Table 1 indicates that ship operation experts constituted the largest group of respondents (30%), highlighting the emphasis on operational knowledge in identifying practical risks. Shipbuilding engineers (24%) contributed technical perspectives, while safety and risk experts (20%) emphasized systematic hazard management. Academics and researchers (14%) provided theoretical and methodological viewpoints, and regulators (10%) offered policy-oriented insights.

3.2Analytical Toolsincluded Python (pandas, matplotlib) for quantitative data processing, producing both descriptive statistics and graphical outputs. SPSS software was employed to conduct reliability analysis and cross-tabulation of expert responses. Additionally, qualitative comments from the survey were coded thematically, allowing for integration of narrative insights into the risk assessment framework. These combined methods ensured both rigor and richness in the findings.

3.3This methodological approach has been similarly emphasized in recent studies [6], [7], [8] which validate the integration of expert survey methods with gap analysis for maritime hydrogen safety.

Experts were asked to score each domain on a scale of 1 to 5. The ideal score of 5 represents complete readiness, while lower scores indicate deficiencies. The difference between the expert score and the ideal value is recorded as the gap. A higher gap value highlights areas requiring urgent improvement. By aggregating across multiple expert responses, the analysis not only quantifies technical and operational weaknesses but also highlights perception-based risks, which are often overlooked in conventional assessments. This dual view of technical and human-centered gaps provides a comprehensive evaluation framework.

The Gap Index (GI) is computed as follows:

(1) $GI_i = \sum (5 - x_{ij}) / n$

where x_{ij} is the score given by expert j for factor i, and n is the number of experts.

The overall structure of the research methodology is illustrated below in Fig. A. It shows the sequential process of literature review, survey design, expert feedback, gap analysis, and synthesis of recommendations. This flow ensures methodological rigor and practical relevance.

A hybrid method was employed. FMEA rated risks by severity, occurrence, and detectability. HAZID workshops explored potential hazards in storage and bunkering scenarios. An expert survey of 49 professionals from marine safety, naval engineering, and fuel system operations contributed perception data. Responses included Likert-scaled ratings and qualitative inputs.

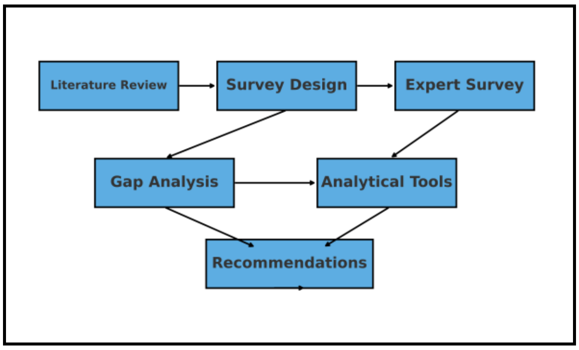

Fig. A. flowchart of the research methodology process

IV. RESULTS AND DISCUSSION

The expert survey revealed tank rupture, bunkering leaks, and training inadequacies as top concerns. These perceptions matched FMEA outcomes, where top RPN values were assigned to these failure modes.

4.1 FMEA Results

The results of the FMEA highlighted the disproportionate risk associated with valve malfunctions and tank ruptures. Although sensor reliability issues scored slightly lower in terms of RPN, expert commentary suggested that early warning failures could escalate incidents rapidly, turning minor leaks into significant safety threats. This finding underlines the importance of redundancy in leak detection systems and consistent calibration protocols.

The analysis of failure modes using the FMEA methodology reveals distinct patterns in risk perception and potential system vulnerability. Fig. 1 presents the top five failure modes ranked by their Risk Priority Number (RPN), with valve malfunction during hydrogen transfer operations receiving the highest score. This indicates that even routine operations like fuel transfer, if unmonitored or under-regulated, can represent considerable threats. Experts attribute high severity to tank rupture and sensor failure due to their possibility of triggering secondary incidents like explosion or undetected leaks. These risks emphasize the critical need for integrated safety mechanisms that include redundancy in valves and real-time diagnostics.

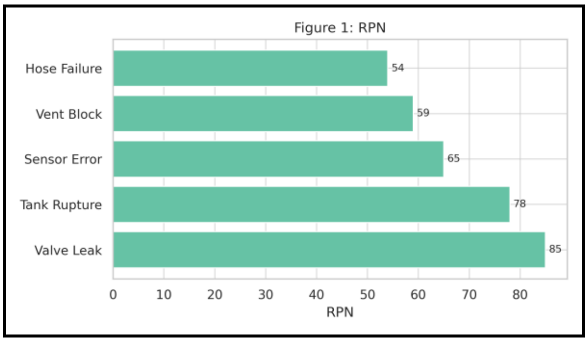

Fig. 1. top 5 risk priority number (rpn) failures from expert perception.

4.2 Concern Levels

Experts expressed substantial concerns about system sensor failures and undetected leaks. The survey showed 93% concern with tank safety and 78% with training programs.Survey data on concern levels revealed consensus among experts that structural integrity and human preparedness are equally important. While tank design is critical, respondents emphasized that even the most advanced containment systems are ineffective without properly trained personnel. The results indicate that investment in technical infrastructure must go together with capacity building initiatives.

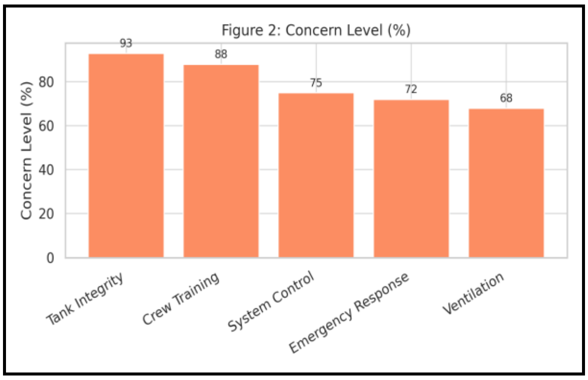

Fig. 2. critical concern areas identified by experts

4.3Extended Concerns

The extended concerns highlighted by experts broaden the scope of traditional risk assessment. While FMEA results pointed to technical failures such as valve malfunctions or sensor reliability, the open-ended responses revealed systemic issues that often lie outside the immediate engineering domain.

Fire response readiness was the most frequently cited concern, reflecting the high flammability of hydrogen and the lack of specialized firefighting protocols tailored for cryogenic fuels.

Bunkering operations were also emphasized as high-risk moments in the hydrogen fuel cycle, with experts noting the absence of harmonized international standards for bunkering procedures.

Training gaps appeared consistently in responses, underscoring that crew preparedness is a decisive factor in whether incidents escalate into full-scale emergencies.

Sensor reliability, though also captured in quantitative scoring, gained more nuanced emphasis in narrative comments, especially regarding the need for redundancy and cross-verification in detection systems.

Lastly, regulatory uncertainty was highlighted as a persistent barrier, where national and international frameworks remain fragmented. Collectively, these extended concerns suggest that risk management for maritime hydrogen must move beyond technical design to encompass regulatory alignment, operational practices, and institutional capacity building.

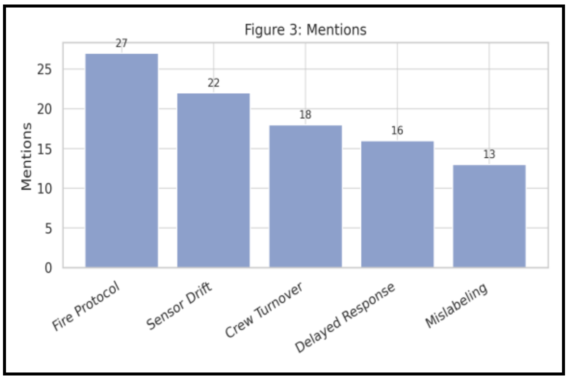

Fig. 3. extended safety concerns from open-ended survey input

4.4Prioritization of safety domains

The prioritization of safety domains, as shown in percentage distribution, demonstrated clear expert preference for focusing on tank integrity and crew training. This prioritization confirms that addressing a small number of critical areas could yield outsized improvements in overall safety performance.

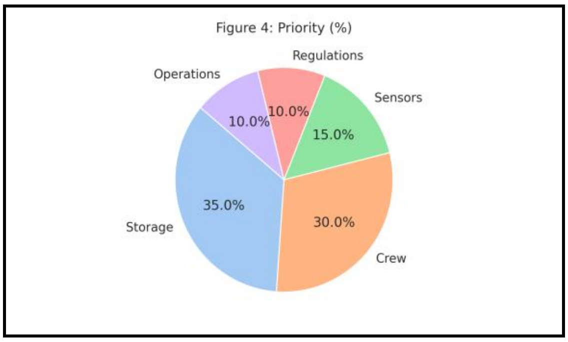

Fig. 4. percentage of priority safety domains

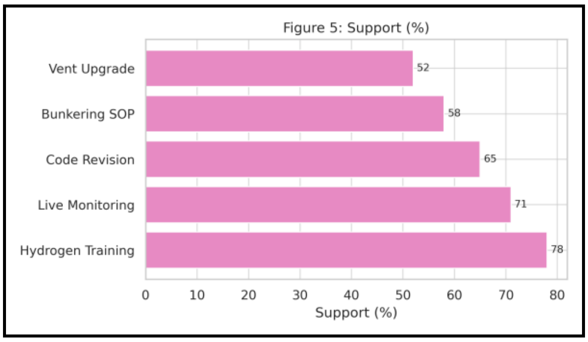

Fig.5. expert-recommended risk mitigation measures

4.5Recommendations

The recommendations provided by experts provide actionable pathways for closing the safety gaps identified in earlier analyses. Hydrogen-specific training programs received the highest level of support, reinforcing the notion that seafarers must be equipped with knowledge tailored to the unique risks of hydrogen, rather than extrapolating from conventional fuel experience. Real-time monitoring systems were also strongly endorsed, with experts pointing to digital innovations and IoT-based sensors as promising tools for early detection and intervention. Updated regulations ranked third, underscoring the importance of developing consistent and internationally harmonized safety codes to reduce operational uncertainty. Finally, while emergency protocols were ranked lowest, they remain crucial in ensuring that once an incident occurs, escalation is contained swiftly. Together, these recommendations outline a multi-pronged strategy where technology, regulation, and training must advance in parallel.

The most supported solutions included real-time monitoring systems (71%) and training enhancements (78%). Regulatory updates were also considered crucial by 68% of respondents.

V. LIMITATIONS

The study has several limitations that should be acknowledged. First, the expert survey was limited to 49 participants, which, while valuable, may not fully capture the diversity of perspectives across different regions, vessel types, and operational contexts. Second, the applied gap analysis and FMEA approach relies heavily on expert judgment, introducing the possibility of subjective bias. Third, the evolving regulatory environment for hydrogen as a marine fuel means that some emerging standards and policies were not fully integrated into this study. Lastly, the qualitative concerns expressed by experts, although highly informative, are open to interpretation and may vary depending on the respondents' backgrounds and professional experiences. These limitations suggest the need for future studies that combine expert-based assessments with empirical operational data and broader stakeholder engagement.

VI. CONCLUSION

In conclusion, the paper makes several significant contributions. It demonstrates how a hybrid methodology can combine the rigor of FMEA and HAZID with the nuanced insights of expert surveys, offering a more comprehensive perspective on hydrogen safety in maritime operations. The results highlight the dual importance of tank integrity and crew training as critical safety domains, while also acknowledging monitoring systems and emergency response as indispensable supporting mechanisms.

Regulatory readiness, consistent with findings by Bucelli et al. [33], is recognized as a foundational enabler for successful hydrogen adoption. Furthermore, the extended concerns raised by experts, including bunkering safety, sensor reliability, and international regulatory harmonization, underscore the necessity of addressing not only technical challenges but also organizational and institutional barriers.

Although this study is limited by its reliance on expert perception and a relatively modest sample size, it provides a structured framework for identifying and prioritizing safety gaps. Future research should incorporate empirical accident data, pilot-scale demonstrations, and cross-national collaboration to validate and refine the findings.

Ultimately, this research offers timely guidance for policymakers, shipbuilders, and maritime operators, supporting the establishment of robust safety standards, specialized training programs, and integrated management systems essential for advancing the safe and sustainable transition to hydrogen-powered maritime transport.

REFERENCES

[1]. M. Al-Enazi, H. Almansoori, and R. Al-Durra, Hydrogen as a sustainable fuel in maritime transport: opportunities and safety challenges, International Journal of Hydrogen Energy, vol. 46, no. 45, 2021, 23210–23222.
[2]. DNV, Maritime Forecast to 2050: Energy Transition Outlook – Hydrogen as a Fuel in Shipping (DNV GL, 2022).
[3]. H. Li, Y. Zhang, and X. Wang, A Bayesian network approach to hydrogen risk assessment in maritime applications, Reliability Engineering & System Safety, vol. 230, 2025, 109067.
[4]. N. Kahlouche, S. Yildiz, and A. Hebbar, Maritime safety in the era of decarbonization: a safety barrier analysis, European Safety and Reliability Conference, 2022.
[5]. SNAME, Guide for Hydrogen as Marine Fuel: Safety and Risk Assessment Guidelines (Society of Naval Architects and Marine Engineers, 2021).
[6]. G. Di Ilio, C. Georgopoulou, and C. Di Maria, On the identification of regulatory gaps for hydrogen as maritime fuel, Sustainable Energy Technologies and Assessments, vol. 75, 2025.
[7]. M. Yazdi, R. Moradi, R.G. Pirbalouti, E. Zarei, and H. Li, Enabling safe and sustainable hydrogen mobility: circular economy-driven management of hydrogen vehicle safety, Processes, vol. 11, no. 9, 2023, 2730.
[8]. Al-Enazi, A., Okonkwo, E. C., Bicer, Y., & Al-Ansari, T. (2021). A review of cleaner alternative fuels for maritime transportation. Energy Reports, 7, 1962-1985.
[9]. Anderson, M., Salo, K., & Fridell, E. (2015). Particle and gaseous emissions from an LNG-powered ship. Environmental science & technology, 49(20), 12568-12575.
[10]. Aneziris, O., Gerbec, M., Koromila, I., Nivolianitou, Z., Pilo, F., & Salzano, E. (2021). Safety guidelines and a training framework for LNG storage and bunkering at ports. Safety Science, 138, 105212.
[11]. Aneziris, O., Koromila, I., &Nivolianitou, Z. (2020). A systematic literature review on LNG safety at ports. Safety Science, 124, 104595.
[12]. Arefin, M. A., Nabi, M. N., Akram, M. W., Islam, M. T., & Chowdhury, M. W. (2020). A review on liquefied natural gas as fuels for dual fuel engines: Opportunities, challenges and responses. Energies, 13(22), 6127.
[13]. Baalisampang, T., Abbassi, R., Garaniya, V., Khan, F., & Dadashzadeh, M. (2019a). Accidental release of Liquefied Natural Gas in a processing facility: effect of equipment congestion level on dispersion behaviour of the flammable vapour. Journal of Loss Prevention in the Process Industries, 61, 237-248.
[14]. Baalisampang, T., Abbassi, R., Garaniya, V., Khan, F., & Dadashzadeh, M. (2019b). Modelling an integrated impact of fire, explosion and combustion products during transitional events caused by an accidental release of LNG. Process Safety and Environmental Protection, 128, 259-272.
[15]. Blume, K. J. (2011). Historical dictionary of the US maritime industry. Scarecrow Press.
[16]. Fan, H., Enshaei, H., & Jayasinghe, S. G. (2021). Safety philosophy and risk analysis methodology for LNG bunkering simultaneous operations (SIMOPs): A literature review. Safety Science, 136, 105150.
[17]. Litvinenko, V. (2020). Digital economy as a factor in the technological development of the mineral sector. Natural Resources Research, 29(3), 1521-1541.
[18]. Mallouppas, G., & Yfantis, E. A. (2021). Decarbonization in shipping industry: A review of research, technology development, and innovation proposals. Journal of Marine Science and Engineering, 9(4), 415.
[19]. Mishra, S., & Mishra, K. B. (2021). Numerical study of large-scale LNG vapour cloud explosion in an unconfined space.

Process Safety and Environmental Protection, 149, 967-976.
[20]. Shen, R., Jiao, Z., Parker, T., Sun, Y., & Wang, Q. (2020). Recent application of Computational Fluid Dynamics (CFD) in process safety and loss prevention: A review. Journal of Loss Prevention in the Process Industries, 67, 104252.
[21]. Temarel, P., Bai, W., Bruns, A., Derbanne, Q., Dessi, D., Dhavalikar, S., Fonseca, N., Fukasawa, T., Gu, X., &Nestegård, A. (2016). Prediction of wave-induced loads on ships: Progress and challenges. Ocean Engineering, 119, 274-308.
[22]. Thomson, H., Corbett, J. J., & Winebrake, J. J. (2015). Natural gas as a marine fuel. Energy Policy, 87, 153-167.
[23]. Wood, D. A. (2012). A review and outlook for the global LNG trade. Journal of Natural Gas Science and Engineering, 9, 16-27.
[24]. Woodward, J. L., &Pitbaldo, R. (2010). LNG risk based safety: modeling and consequence analysis. John Wiley & Sons.
[25]. Abdalla, A. M., Hossain, S., Nisfindy, O. B., Azad, A. T., Dawood, M., & Azad, A. K. (2018). Hydrogen production, storage, transportation and key challenges with applications: A review. Energy conversion and management, 165, 602-627.
[26]. Action, C. (2013). Support for the impact assessment of a proposal to address maritime transport greenhouse gas emissions.
[27]. Ait Aider, C. (2022). Integration of a tank storage solution for alternative fuels on a RoRo ship University of Rostock, University of Liège].
[28]. Alamoush, A. S., Ölçer, A. I., &Ballini, F. (2022). Ports' role in shipping decarbonisation: A common port incentive scheme for shipping greenhouse gas emissions reduction. Cleaner Logistics and Supply Chain, 3, 100021.
[29]. Jeong, J., Choi, M., You, H., & Chang, D. (2025). Comparative risk assessment of gaseous and liquid hydrogen fuel gas supply systems for hydrogen-fueled vessels. Journal of Ocean Engineering and Science. Elsevier.
[30]. Duong, P.A., Bae, J.W., Lee, C., & Yang, D.H. (2025). Numerical study on ammonia dispersion and explosion characteristics in confined space of marine fuel preparation room. Journal of Marine Science and Engineering, 13(7), 1235. MDPI.
[31]. Koromila, I., Nivolianitou, Z., & Aneziris, O. (2025). A systematic literature review on safety of hydrogen as a marine fuel. Chemical Engineering Transactions, 116, 122.
[32]. Kang, J., Su, T., Dai, H., Jin, H., & Chen, Y. (2025). Risk analysis of hydrogen leakage from hydrogen fuel cell ships based on bidirectional reasoning mechanisms. Ocean Engineering. Elsevier.
[33]. Bucelli, M., Zanobetti, F., & Schiaroli, A. (2025). Accident scenarios for safety risk management of ammonia fuelled ships. Proceedings of the 35th European Safety and Reliability Conference. NTNU.