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Challenges and Paths of Hydrogen Energy Transportation Risk Management from a Full Life Cycle Perspective

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ABSTRACT

Under the impetus of the dual carbon strategy, hydrogen energy faces a critical transport bottleneck due to high costs and safety risks, intensified by hydrogen's extreme flammability, wide explosive limits, and metal embrittlement. This study introduces lifecycle management into hydrogen transport safety, systematically identifying key risks across high-pressure tube trailers, liquid hydrogen tankers, pipelines, and solid-state storage, and analyzing accident mechanisms including fatigue failure, hydrogen embrittlement cracking, vapor flash ignition, and vacuum failure, with emphasis on amplification effects in tunnels and refueling station unloading. The root cause is identified as fragmented management and information silos across production, transport, utilization, and disposal, enabling risk propagation without full-lifecycle accountability. A three-dimensional strategy is proposed: technologically, dynamic risk models using connected vehicle data and active leak defense like acoustic detection and catalytic abatement; managerially, lifelong electronic equipment archives and closed-loop handover information flows; institutionally, green design and recycling standards aligned with dual carbon goals, plus carbon trading to incentivize safety upgrades. Breaking cross-chain barriers and building a safety narrative from inception to decommissioning for every asset is fundamental to achieving intrinsic hydrogen transport safety.

KEYWORDS

Dual carbon goals; Hydrogen transport; Risk assessment; Full life cycle management; Safety management

1. INTRODUCTION

The proposal of the "dual carbon" strategy marks that China's economic and social development has entered a new stage with green and low-carbon as the core driving force. The underlying logic lies in reshaping the energy system based on fossil energy and building a new energy system with wind, solar and other renewable energy sources as the main body. The difficulty of this transformation lies not in a single technological breakthrough, but in whether the entire system can operate safely, stably and economically. In the face of the intermittency and volatility of wind and solar power, a large-scale energy regulation tool - hydrogen - is thus leaping from an industrial raw material to a core piece in the national energy strategy.

Hydrogen has an almost irreplaceable mission: it is the best path to deep decarbonization in areas where electricity is hard to reach, such as steel, chemicals, and heavy transportation; At the same time, it can convert unstable green electricity into chemical energy that can be stored for a long time, acting as a "stabilizer" for new power systems. By the time carbon neutrality is achieved in the middle of this century, China's annual demand for hydrogen will account for nearly one-fifth of terminal energy consumption and become a basic energy commodity in circulation across the country.

However, the realization of this grand vision depends on the weakest links. Looking at the entire industrial chain of "hydrogen production - storage - transportation - refueling - application", the storage and transportation links are becoming the fatal bottleneck that restricts the overall situation. China's high-quality green hydrogen resources are concentrated in the northwest deserts, and the core demand is in the eastern coastal areas. This spatial mismatch determines that hydrogen must undergo large-scale and long-distance circulation. The extreme physical and chemical properties of hydrogen itself - extremely flammable, with an explosive limit of 4% to 75.6%, highly prone to leakage and causing "hydrogen embrittlement", and flames invisible to sunlight - make transportation inherently a high-risk activity. When the scale of transportation jumps from millions of tons to hundreds of millions of tons, safety issues will be elevated to a complex system public safety challenge.

The current mainstream high-pressure long tube trailers for hydrogen transport have a seriously insufficient economic transport radius; Efficient liquid or pipeline hydrogen transportation is constrained by technical equipment "choke points", huge infrastructure investment and a lack of regulatory standards. This is the starting point of the study: In the era of large-scale, long-distance transportation, we cannot follow the fragmented management of treating symptoms rather than root causes, but must re-examine the safety risks and governance paths of hydrogen transportation from a life-cycle perspective.

2. LITERATURE REVIEW

2.1. Status of Research on Hydrogen Transport Safety

The safety of hydrogen transportation is a key issue that has emerged as the hydrogen industry transitions from the chemical sector to the energy sector. Around this topic, scholars at home and abroad have carried out a large amount of work from different technical routes and different research perspectives, forming an increasingly rich but still clearly divided knowledge picture.

2.1.1. Experimental and Simulation Studies on Core Storage and Transportation Technologies Abroad

Abroad, particularly in leading economies such as the United States, Japan, and Europe, research on hydrogen storage and transportation focuses on precisely defining safety boundaries for critical processes through high-cost experiments and high-performance numerical simulations.

Regarding high-pressure gaseous tube trailers, the focus lies on hydrogen embrittlement mechanisms of materials and simulation of leakage and combustion behavior. San Marchi and Somerday (2012) [1] from Sandia National Laboratories in the United States systematically reviewed the effects of hydrogen on the mechanical properties of metallic structural materials, laying the foundation for material selection in hydrogen storage containers. Accident consequence simulations are predominantly based on CFD methods: Hussein et al. (2010) [2] simulated the jet flame resulting from a small hole leak of high-pressure hydrogen, quantifying the spatial distribution of flame length and thermal radiation; Li et al. (2021) [3], placing the scenario within a tunnel, revealed the amplifying effect of semi-enclosed spaces on the consequences of combustible gas cloud explosions.

Regarding liquid hydrogen tank trucks, research challenges focus on vapor management and low-temperature brittleness caused by extreme cold and high evaporation rates. Schmidt et al. (2012) [4] from the German Federal Institute for Materials Research conducted large-scale liquid hydrogen leakage experiments to observe the unique behavior of cryogenic hydrogen clouds spreading along the ground. Verfondern (2008) [5] systematically compared the fundamental differences in leakage, evaporation, and combustion characteristics between liquid hydrogen and conventional fuels. Ichard et al. (2012) [6] used a CFD model to simulate multiphase flow and phase change processes during liquid hydrogen leaks, validating the effectiveness of numerical simulations.

In the field of pipeline hydrogen transportation, research has focused on the feasibility of hydrogen blending in natural gas pipelines and the material compatibility challenges associated with pure hydrogen pipelines. The EU NaturallHy project (Florisson et al., 2010) [7] evaluated the impacts of hydrogen blending on pipes, equipment, and end-use systems, concluding that low-level blending is technically feasible but requires case-by-case assessment. Arafah and Bock (2018) [8] used finite element methods to simulate crack propagation behavior in defective pipeline steel under high-pressure hydrogen, providing a modeling foundation for pipeline safety assessments.

2.1.2. Domestic Progress in Regulatory Standards and Qualitative Risk Analysis

In contrast to the technology-oriented approach abroad, research in the domestic academic and industrial sectors has been strongly policy and institutional responsive from the very beginning, with a focus on the construction of macro regulatory and standard systems and qualitative risk assessment based on expert experience.

In terms of the research on the regulatory and standard system, domestic scholars are committed to sorting out and constructing a system framework that is suitable for the industrialization development of hydrogen energy. The team of Academician Zheng Jinyang is a pioneer in the safety research of high-pressure hydrogen storage containers in China. The early review work of the team (such as Zheng et al., 2012) [9] systematically compared the gap between China's standards for high-pressure hydrogen storage equipment and those of Europe, the United States and Japan from multiple dimensions including materials, design, manufacturing and inspection, and proposed a roadmap for the construction of the standard system. Since then, with the acceleration of the industrialization process, more and more research has focused on the "fragmentation" and "lag" of the regulatory standard system. For example, Wang et al. (2020) [10] clearly pointed out a key contradiction in their policy research: the positioning of hydrogen in the hazardous chemicals management catalogue makes it face multiple institutional obstacles in land approval, road access, station construction and other links when transported on a large scale and in a networked manner as an energy commodity. These studies have jointly contributed to the industry consensus that China needs to establish a safety governance system that is distinct from traditional hazardous chemicals management and specifically targeted at the hydrogen energy industry.

In terms of qualitative risk analysis, due to the lack of large-scale hydrogen safety experimental conditions and accumulated failure data in the country, a large number of studies have adopted qualitative or semi-qualitative methods based on expert knowledge, logical deduction and systematic analysis. HAZOP analysis is one of the most widely used tools. Several scholars, such as Zhang Li et al. (2019) [11], conducted HAZOP analysis on the entire unloading process of hydrogen tube bundle vehicles at a hydrogen refueling station, systematically identified scenarios that could lead to leakage, such as pipeline connection failure, valve misoperation, and pressure relief system failure, and proposed corresponding safety interlock and operating procedure suggestions. In addition, fault tree analysis, pre-hazard analysis and analytic hierarchy process were also widely used to comprehensively assess the relative risks of different modes of transport (long tube trailers, liquid hydrogen tankers). For example, Li Ming et al. (2021) [12] used the Analytic Hierarchy Process to construct an evaluation system including indicators such as technical maturity, severity of accident consequences, and completeness of regulations to rank the safety risks of various hydrogen transport modes comprehensively and concluded that the comprehensive risk of liquid hydrogen transport is higher than that of high-pressure gas hydrogen under the current national conditions. Although these qualitative studies could not provide precise accident probabilities and consequence values, they played a crucial foundational role in systematically constructing risk cognition maps and identifying key risk control nodes.

2.2. Review of Existing Research and Positioning of This Study

In summary, current research presents an intriguing "puzzle." Western academic contributions mostly consist of "technical details," meticulously depicting the physical risk scenarios in specific contexts through precise experiments and models. However, their perspectives often stop at the moment of accident occurrence, lacking attention to the full-chain evolution logic of risks from their origin to ultimate outbreak. In contrast, domestic studies primarily focus on "institutional frameworks," mapping macro-level risk perceptions using qualitative methods. Yet these studies are relatively weak in quantifiability and dynamic risk perception, frequently criticized as mere theoretical discussions.

The most significant gap in this puzzle lies precisely in "connection" and "throughout integration." On one hand, there is a lack of an analytical framework capable of linking micro-scale damage during the early life stages of equipment (design and manufacturing) with macro-scale failures in later stages (operation and aging), as well as connecting instantaneous accidents during transportation with routine operational errors across the upstream and downstream segments of the supply chain. On the other hand, existing research pays insufficient attention to safety and environmental concerns regarding the final stage of hydrogen transport equipment—retirement and disposal—resulting in a break at the end of the lifecycle management chain. This is exactly where this study intervenes. Rather than competing with prior work in depth on isolated technical details or regulatory provisions, this study introduces the concept of lifecycle management, integrating fragmented technical, managerial, and policy research into a coherent analytical framework. It systematically examines the mechanisms by which risks emerge, propagate, and evolve throughout the entire "cradle-to-grave" lifecycle of hydrogen storage and transportation equipment, thereby addressing the shortcomings of existing research in terms of systemness, dynamism, and completeness.

3. CORE ISSUE

The structural contradiction between traditional management models and scalable risks

Based on the current research situation at home and abroad, it is evident that there is a common perspective limitation in existing work: whether it is the exploration of hydrogen embrittlement mechanism, the simulation of leakage diffusion, or the formulation of standards and norms, the "lens" of risk examination mainly focuses on the transportation process itself - the period when the vehicle is in transit. This "sliced" thinking separates the transportation process from "the entire life of the equipment" and "the entire industrial chain", making it difficult to answer the key question of whether the underlying cause of a certain leakage accident can be traced back to the initial internal damage caused by a non-compliant filling of the gas cylinder three years ago? The weight gain and efficiency loss of equipment caused by the layering of safety margins to reduce the accident rate by one in ten thousand actually created net safety value throughout the entire life cycle?

When hydrogen transportation evolved from a niche activity around chemical industrial parks to a high-frequency energy delivery network covering urban and rural areas across the country, the contradiction between this limited perspective and the surge in scale intensified sharply. Exposure to risks amplifies as the number of vehicles and frequency increase; Accident scenarios expand from factory leaks to complex public Spaces such as tunnels, Bridges, and downtown areas; More fundamentally, the traditional segmented management - transport pipes for transportation, fill pipes for filling, and hydrogen pipes for unloading - will create a breeding ground for systemic risks due to information breakdowns and ambiguous responsibilities. The hidden damage to a tanker cylinder may start with non-compliant filling, deteriorate through long bumpy rides, and eventually be exposed to unloading operations in downtown areas, with no one being continuously responsible for the health status of the cylinder throughout its entire life cycle.

Hydrogen station explosions and tank accidents that have occurred in Norway, the United States, South Korea and other places in recent years have repeatedly warned that every disaster is not an isolated accident, but a concentrated collapse resulting from the accumulation of material failures, operational errors and oversight in management gaps. This has torn apart overly optimistic safety assumptions and exposed the deep chasm between intrinsic safety requirements and fragmented management.

As a result, the core issue of this study becomes clear: In the context of the "dual carbon" strategy driving hydrogen transportation towards scale and networking, the traditional safety management model oriented towards process compliance and responsible for each link has become difficult to effectively address the systemic challenges brought about by the multiple hazards of hydrogen. There is an urgent need for a life-cycle risk management perspective and approach that can penetrate the entire process of equipment from manufacturing to decommissioning, dynamically perceive the evolution of risks, and seamlessly connect the responsibilities of each link.

4. RESPONSE STRATEGIES AND RECOMMENDATIONS

4.1. Technical Aspect: Strengthening Risk Assessment and Intelligent Monitoring

Technology is the first line of defense for managing risks. The current shortcoming of hydrogen transport safety technology is not the lack of means, but the static and fragmented nature of means. There are two directions to break through.

One is to build a dynamic quantitative risk assessment model based on real-time Internet of Vehicles data. Traditional risk assessment is a static report based on assumed operating conditions and general failure data, and once written, it has no connection with the actual vehicle on the highway. The future technological path should be to turn every hydrogen tanker into a flowing data node. The real-time pressure and temperature of the gas cylinder, the vacuum degree of the vacuum insulation layer, the vehicle's speed and GPS location, the cumulative number of charge and discharge and the vibration and shock load - these data are sent back to the cloud in real time via the Internet of Vehicles. A dynamic risk assessment model is always online, not content with answering "How risky is this type of vehicle?" but continuously calculating the real-time risk value of "this vehicle, at this moment, in this position, and under this condition." When the model determines that the risk curve is climbing abnormally - for example, the fatigue damage factor of a certain gas cylinder is approaching the warning threshold, or the vacuum decline trend is suddenly accelerating - the system automatically sends graded warnings to the driver and the monitoring center and dynamically suggests slowing down, stopping nearby for inspection, or changing routes. This will shift safety decisions from "post-event traceability" to "pre-event intervention".

The second is to develop rapid hydrogen leak detection and explosion suppression technologies. The fatal thing about hydrogen leaks is that they can't be seen, heard or smelled. Traditional point gas sensors have response delays and can only detect leaks near the point where the probe is installed. Acoustic wave detection technology offers a new approach to this problem. When high-pressure hydrogen is ejected from tiny cracks, it generates high-frequency sound waves of specific frequencies that travel along the container walls or pipes. Deploying acoustic emission sensor arrays at critical nodes can capture abnormal signals and precisely locate leaks within milliseconds of their occurrence, with a response speed far exceeding that of traditional concentration-type sensors. Detecting a leak is just the first step; more proactive measures are to suppress it before an explosion occurs. Catalytic dehydrogenation technology, by placing precious metal catalysts in the potential leak space, enables the leaked hydrogen to react smoothly with oxygen in the air to form water when the concentration is far below the lower limit of the explosion, cutting off the accumulation process of the combustible gas cloud from the root. This technology, which has been well applied in hydrogen safety control at nuclear power plants, is now being transplanted into hydrogen infrastructure. The dual protection of sound wave "hearing" leaks and catalytic "eliminating" hydrogen can advance the accident defense line from passive isolation to active elimination of hazard sources.

4.2. Management Level: Weaving a Full Life Cycle Supervision Network

No matter how good the technology is, it can still be a mere decoration without a strict management system to link it together. The core task at the management level is to break the current fragmented pattern of links and subjects and weave a regulatory network that covers the entire life cycle of equipment.

The foundation of this network is the implementation of a lifetime electronic file system for one vehicle, one bottle, one tube. Give each hydrogen storage pressure vessel, each transport vehicle, and each hydrogen pipeline a unique digital identity, and enforce the recording of key data throughout the entire life cycle from manufacturing, each filling, regular inspection to retirement. Material furnace batch numbers and weld flaw detection negatives at the time of manufacturing, pressure-temperature curves and transport vibration and shock loads at each filling during service, thickness measurement data and crack detection results at each periodic inspection - this information is no longer scattered in the archives of each manufacturing plant, filling station, logistics company and inspection agency. Instead, they are aggregated on a unified, unalterable blockchain-based data platform. This will fundamentally change the current security management logic: in the past, we could only painstakingly trace the entire life of a gas cylinder after an accident, but in the future, its entire life trajectory will always follow it, and any abnormality in any link will not be erased by the flow.

On the basis of the lifetime file, it is necessary to clarify the safety responsibility handover standards and information flow for filling, transportation and unloading. The biggest management gray area at present lies in the "interfaces" between links. Does the filling station confirm that the gas cylinders are in a qualified state before and after filling them with high-pressure hydrogen? Does the transport company read all the data from the previous stage when it receives the vehicle? Did it verify what abnormal conditions had occurred during the journey before unloading at the hydrogen refueling station? The recommendation of this study is to define each handover as a mandatory "safe handshake" procedure: the upstream link must package the key data of this operation and the real-time health status of the equipment to generate a digital handover sheet, and the downstream link must verify it before receiving it, and refuse to accept it if the verification fails. Only when responsibility is passed through without breakpoints at every interface can the full life cycle regulatory network be truly closed.

4.3. Institutional Level: Improve Standards and Green Exit Mechanisms

The implementation of technology and management ultimately requires the system to provide a rule-based and market-driven basis. The institutional response strategy focuses on addressing the two major shortcomings in the current standard system: "missing ends" and "insufficient incentives".

The first is to introduce technical standards for green design and recycling of high-pressure gas cylinders, liquid hydrogen containers and hydrogen pipelines for the "dual carbon" goals. The current standard system focuses almost entirely on the design, manufacturing and in-service inspection stages of equipment, and has almost no regulations on the recycling of equipment after retirement. In the case of carbon fiber wound high-pressure gas cylinders, there are neither mandatory safety disposal norms nor encouraging guidelines for recycling and reuse when they are scrapped. Carbon fiber is expensive but difficult to recycle. Incineration produces toxic waste gas and landfilling causes a permanent environmental burden, which is seriously contrary to the green intention of "dual carbon". The system must extend both forward and backward. Forward means establishing green design standards that require future new production of gas cylinders and containers to take into account disassemblability and recyclability of materials at the design stage. Backward, establish mandatory technical standards for decommissioning and recycling, specifying safe scrapping procedures, recycling process specifications, and environmental emission limits. Only when "decommissioning disposal" is incorporated into the institutional mandatory constraints can the full life cycle management form a complete closed loop.

The second is to use market mechanisms such as carbon trading to encourage enterprises to proactively update high-safety and recyclable transport equipment. Relying solely on executive orders to drive companies to upgrade their equipment often leads to cost resistance and passive response. The market mechanism can translate the external benefits of safety and greenness into internal economic gains for enterprises. One feasible approach is to account for the lightweight and recyclable design of hydrogen transport equipment, as well as the risk reduction effect achieved by enterprises through the adoption of intelligent monitoring systems, as quantifiable carbon reduction indicators or safety credit points, and incorporate them into carbon trading markets or safety rating systems. Enterprises that proactively phase out high-risk, high-energy-consuming old equipment and are the first to adopt a full life-cycle management system can receive carbon quota discounts, insurance fee reductions or green credit support. This will completely change the behavioral motivation of enterprises in safety management: safety will no longer be a cost center that is forced to comply, but a value center that can create a competitive advantage.

5. CONCLUSIONS AND PROSPECTS

5.1. Main Conclusions

In the context of the "dual carbon" strategy, this study systematically examines the risk characteristics and management challenges in the hydrogen transportation sector. The following core conclusions can be distilled from the analysis.

First, the risks of hydrogen transportation are not scattered and isolated, but highly concentrated in a few typical technical nodes. High-pressure gas long tube trailers face a triple threat of fatigue failure, hydrogen embrittlement burst and collision ejection fire, with tunnel and hydrogen refueling station unloading scenarios being the extreme amplifiers of these risks. The risks of liquid hydrogen tanker transportation revolve around ultra-low temperatures, frostfreezing, evaporative flash explosion, and rapid pressurization after the failure of the vacuum insulation layer form a unique risk triangle. The core challenge of pipeline hydrogen transportation, whether blended or pure, lies in the destruction of hydrogen's compatibility with the material, and the risk has systemic characteristics of being deeply buried underground, silently accumulating, and irreversible once it occurs. Emerging technologies such as solid-state hydrogen storage are not synonymous with intrinsic safety; they merely transform risks from high-pressure leaks into new forms of thermal management and material activity. The concentration of these risk points forms a list of challenges for hydrogen transport safety management.

Second, and the core assertion of this study: The essence of the full life cycle management concept lies in breaking down the long-standing management barriers between "production - transportation - use - waste". The current safety management is systemically divided into multiple independent links such as production, filling, transportation, use, inspection, and scrapping, each of which only takes care of its own "small plot of land". Risk, however, does not recognize such artificial boundaries; it will quietly spread, accumulate and evolve along the industrial chain. A defect in a gas cylinder may arise in manufacturing, deteriorate in filling, lurk in transportation, and eventually explode in unloading. No single link is responsible for the ultimate tragedy, so someone must be responsible for the entire chain. The core of life cycle management is to stitch together these fragmented links with a set of consistent digital archives, a set of seamless handover standards, and a set of institutional norms covering the entire process from design to decommissioning. It is not intended to replace the professional management of each link, but to build a higher-level, cross-link integrated management framework on top of them. This perception is the core idea that this study hopes to contribute to the governance of hydrogen transport safety.

5.2. Research Limitations and Future Directions

This study, as an exploratory work, has several limitations, which in themselves indicate the direction of future research.

First of all, this study has a strong qualitative color. Qualitative methods based on literature analysis and logical deduction were mainly adopted in the construction of the risk identification and full life cycle management framework. This can outline the overall picture of risks, but it cannot provide precise quantitative conclusions. Future research could build on this basis and combine actual road network data, population distribution data and traffic flow data in specific regions to conduct quantitative risk assessment, calculate individual risk and social risk curves for different transport routes and different time periods, and provide numerical basis for specific route selection decisions and safety distance setting.

Secondly, this study has established a conceptual framework for full life cycle management, but has not yet delved into its technical implementation level. The actual implementation of this framework cannot do without the support of emerging information technologies. Looking ahead, the two technologies show great potential in achieving full chain accountability. One is blockchain technology. The immutable, multi-party shared and traceable nature of its data fits precisely the demand for a lifetime electronic file of "one vehicle, one bottle, one tube". The blockchain-based hydrogen transport safety data platform technically ensures that every filling record, every inspection report, and every handover confirmation cannot be tampered with after the fact, truly anchoring responsibility at every link and leaving no room for any attempt to shirk responsibility. Second, artificial intelligence technology. When massive amounts of vehicle operation data, equipment status data and environmental data are aggregated, traditional manual analysis will be inadequate. Machine learning algorithms can automatically identify risk evolution patterns and precursors of faults that are difficult for humans to detect from these seemingly chaotic data, achieving a qualitative change from "passive alarm" to "intelligent early warning". The deep integration of these two technologies with the concept of full life cycle management will be a key step from "safety management" to "modernization of safety governance", worthy of continuous in-depth research and practical exploration.

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