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# Hydrogen Technologies in Rail Transport: A Review of Safety Risks, Risk Management Practices and Regulatory Frameworks

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## Abstract

The introduction of hydrogen technologies into rail transport offers opportunities to reduce emissions from railway operations, particularly on non-electrified lines, but also creates safety challenges related to hydrogen storage, refuelling, vehicle operation and railway infrastructure. This study examines how hydrogen-specific hazards, engineering safeguards and existing railway safety management procedures can be integrated to support the safe implementation of hydrogen technologies in European railway systems. A structured narrative review was conducted using scientific publications, regulatory documents, technical standards and selected institutional reports published between 2009 and 2026. The reviewed material was analysed through qualitative thematic synthesis, focusing on hydrogen-related hazards, railway-specific operating conditions, preventive and mitigating measures, and applicable regulatory requirements. The analysis identifies on-board hydrogen storage failures, hydrogen leakage and accumulation, refuelling operations, ignition sources, maintenance activities and emergency response as principal safety concern areas. It highlights the influence of railway-specific conditions, including vibration, dynamic and crash loads, pressure cycling, restricted ventilation in tunnels and maintenance facilities, passenger presence, and interactions with electrified railway infrastructure. The review also indicates that the European railway safety framework, particularly the Common Safety Method for Risk Evaluation and Assessment (CSM RA) and the RAMS principles, provides a basis for managing safety-related changes, but does not eliminate the need for hydrogen-specific technical evidence and application-specific assessments. The findings identify priorities for further research, railway-specific testing, regulatory development and standardisation. The study provides an integrated qualitative synthesis of hydrogen hazards and railway safety requirements; it does not constitute a quantitative risk assessment.

**Keywords:** hydrogen; railway transport; hydrogen safety; risk assessment; Common Safety Method for Risk Evaluation and Assessment (CSM RA); RAMS; railway safety management; regulatory framework

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## 1. Introduction

Interest in developing and using advanced fuels in the global economy has been fuelled by growing awareness of the limited resources of fossil fuels and the simultaneous need to protect the natural environment. Reducing emissions from the combustion of hydrocarbon fuels, including particulate matter and greenhouse gases (GHGs), has been identified

as particularly important. These emissions contribute to the increase in average global temperature, which is harmful to the planet and people.

Research and development efforts aimed at identifying alternative fuels have also extended to the transport sector, which remains a major source of greenhouse gas emissions in the European Union. The European Green Deal, presented by the European Commission on 11 December 2019, sets out the objective of reducing transport-related greenhouse gas emissions by 90% by 2050 compared with 1990 levels [1]. Available sources indicate [2] that the majority of greenhouse gas emissions emitted by the transport sector come from road transport, including passenger cars, buses, and trucks. Rail's share of total transport emissions is approximately 1%, or approximately 0.2% of total GHG emissions; see Figure 1. Rail transport is therefore considered the least carbon-intensive mode of transport worldwide.

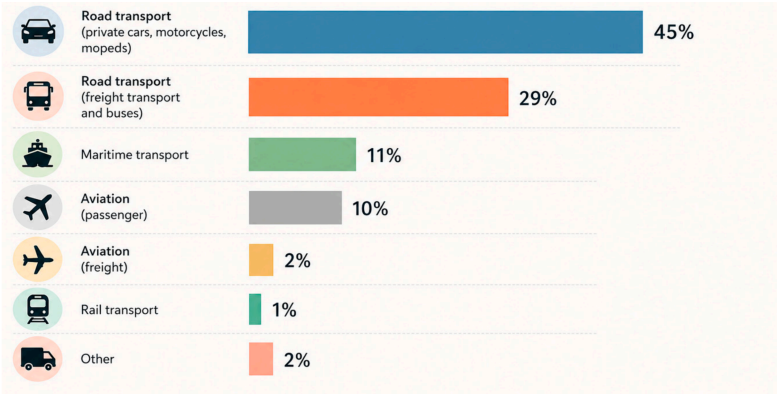
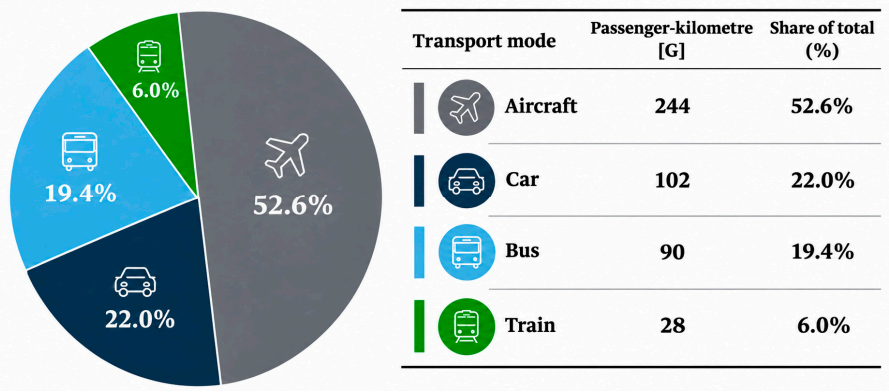



**Figure 1.** Greenhouse gas emissions from the global transport sector. Source: Authors' own elaboration based on [2].

Figure 2 presents average CER (Community of European Railways and Infrastructure) statistics for the amount of carbon dioxide emitted per passenger per km (passenger-kilometres, pkm) for individual modes of transport.




| Transport mode | Passenger-kilometre [G] | Share of total (%) |
|---|---|---|
| Aircraft | 244 | 52.6% |
| Car | 102 | 22.0% |
| Bus | 90 | 19.4% |
| Train | 28 | 6.0% |

**Figure 2.** $CO_2$ emissions per passenger-kilometre for each mode of transport. Source: Authors' own elaboration based on [3].

The integration of environmentally sustainable fuel alternatives into mass transportation systems, particularly those supporting the transition toward a hydrogen economy, remains a major technological challenge. Among the available low-emission energy carriers, hydrogen has emerged as one of the most promising solutions for transport applications [4]. However, the large-scale deployment of hydrogen-powered trains in the railway sector requires overcoming a range of technological and non-technological barriers. In particular, the storage of substantial quantities of hydrogen in on-board tanks raises important

safety concerns and potential hazards, particularly as this would involve high pressures or cryogenic temperatures. Addressing these risks is essential not only for ensuring operational safety but also for obtaining regulatory approval and fostering public acceptance of hydrogen-based rail technologies [1,5].

Despite the above, the railway industry has also actively engaged in the process of decarbonizing transport and improving the sector's environmental performance. Hydrogen fuel cells, lithium batteries, and natural gas have begun to be used in rail vehicles. Hydrogen is gaining the greatest popularity. Its potential as a fuel is enormous due to its unlimited resources (it constitutes 94% of the universe). Furthermore, hydrogen:

- Easily forms a homogeneous combustible mixture (it has a high $H_2$ diffusion coefficient in air);
- Is the lightest fuel in any state;
- Has the highest calorific value per mass (120 MJ/kg);
- Is a highly reactive fuel, characterized by a high octane number and a rapid combustion rate.

The use of hydrogen as a fuel is possible in all types of rolling stock for passenger transport (subways, suburban railways, long-distance railways, high-speed railways), freight transport, and in track maintenance and shunting vehicles, which can make railways even more environmentally friendly. Therefore, in 2003, during a presentation at the Volpe Center for Transportation Systems of the United States Department of Transportation in Cambridge (USA), the term "hydrail" was introduced [6]. However, hydrogen also has disadvantages, including the following:

- it is a colorless and odorless gas, extremely flammable and highly explosive in mixtures with air,
- its flame burning in air at atmospheric pressure is invisible and radiates less heat than a hydrocarbon flame (which is particularly dangerous),
- it causes embrittlement of many common construction metals,
- a leak from the tank can lead to flames, jet fires, deflagration or even detonation,
- the significant disadvantages of hydrogen fuel cells are still their high production costs, reliability and availability.

Furthermore, one of the factors hindering the mass introduction of hydrogen technologies in the rail industry is the lack of standardization of rolling stock and infrastructure designed to ensure operational capacity in passenger and freight transport. Therefore, to enable the use of hydrogen on a larger scale, it is necessary to develop favorable safety, system, and regulatory conditions.

Developing such standards requires defining the risk factors present in the rail system. This means building a safety architecture using current regulations and standards regarding reliability, availability, maintainability and safety, as well as creating a register of key risks.

Safely integrating hydrogen technologies into existing rail safety systems poses a significant challenge, requiring the development of a uniform approach to risk assessment and management throughout the entire lifecycle of these technologies—from reliability, through availability, to maintainability and safety. The development of new technologies always carries risks that require systematic monitoring and continuous verification to ensure the safety and reliability of the entire system. It is important to emphasize that the threats associated with hydrogen technologies impact the safety of life, health, and property, as well as the safety of rail transport. Ensuring an adequate level of safety is crucial for the effective implementation of hydrogen technology in rail transport; therefore, it is necessary to precisely define the safety framework within which hydrogen technologies will be used in the railway sector [7].

Previous studies have addressed hydrogen-powered railway technologies from different perspectives. The safety of hydrogen-powered trains under different application scenarios was reviewed in [1], while [8] examined hydrogen technologies and engineering solutions relevant to railway vehicle design and operation. Other studies have focused on hydrogen storage, leakage, fire and explosion phenomena, refuelling infrastructure, and selected quantitative risk assessment methods.

Although these publications provide an important knowledge base, the relationship between hydrogen-specific hazards and the established European railway safety management and regulatory framework requires further synthesis. In particular, the introduction of hydrogen-powered rolling stock and refuelling infrastructure involves interactions between vehicle systems, storage installations, railway depots, maintenance facilities, operational procedures and emergency response arrangements. These interactions cannot be fully addressed by considering hydrogen-related hazards or engineering solutions independently.

The present study therefore focuses on the integration of three complementary areas:

- Hydrogen-specific technical and operational hazards;
- Railway safety management and risk acceptance procedures;
- Regulatory and standardisation requirements applicable to hydrogen technologies in railway applications.

The main research question addressed in this paper is: How can existing hydrogen safety knowledge, engineering protection measures and railway safety management procedures be integrated to support the safe implementation of hydrogen technologies in European railway systems?

To address this question, the study pursues the following objectives:

- to identify and classify the principal hydrogen-related hazards associated with railway rolling stock, refuelling infrastructure, maintenance facilities, and railway operating environments,
- to examine the applicability of existing railway risk management procedures, particularly the Common Safety Method for Risk Evaluation and Assessment (CSM RA) and RAMS standards, to hydrogen-powered railway applications,
- to analyse the relationship between identified hazards, available engineering safeguards, and applicable railway and hydrogen-related standards,
- to identify regulatory and standardisation gaps that may affect the safety assessment, authorization, operation, and maintenance of hydrogen railway systems,
- to formulate practical recommendations for integrating hydrogen-specific safety evidence into railway safety assessment and approval processes.

The main contribution of this paper is an integrated qualitative synthesis linking hydrogen-related hazards with railway-specific operational conditions, risk management procedures, safety management procedures and regulatory requirements. Unlike reviews focusing primarily on hydrogen-powered vehicle technologies or individual hydrogen safety phenomena, this study places particular emphasis on the interfaces between the safety of hydrogen installations and the established European railway safety framework. The study also develops a structured hazard analysis and regulatory gap mapping approach to support the identification of areas requiring further technical verification, standardisation, and application-specific risk assessment.

The paper is structured as follows. Section 2 describes the literature review methodology. Section 3 examines hydrogen-related hazards in railway applications and presents an integrated qualitative hazard analysis. Section 4 discusses railway safety management procedures and the applicable regulatory and standardisation framework. Section 5 presents

the conclusions, summarises the main findings of the review, identifies the key limitations of the available evidence and outlines priorities for future research.

## 2. Methodology

This study adopts a structured narrative review approach to examine safety risks, railway risk management practices and regulatory requirements associated with the implementation of hydrogen technologies in rail transport. The review combines peer-reviewed scientific publications, technical standards, regulatory documents and selected official institutional reports.

The literature search was conducted using the following sources: Scopus, Web of Science, Eur-Lex, and Google Scholar. The reviewed literature included sources published between 2009 and 2026. The search strategy combined terms relating to hydrogen technologies, railway applications, and safety management.

The principal search terms included combinations of the following keywords: "hydrogen powered trains", "hydrogen railway safety", "hydrogen storage", "hydrogen leakage", "hydrogen refuelling station", "hydrogen explosion", "railway risk assessment", "Common Safety Method", "CSM RA", "RAMS", and "hydrogen railway standards".

The following inclusion criteria were applied:

- publications addressing hydrogen technologies in railway applications,
- studies examining hydrogen-related hazards, leakage, fire, explosion, storage, or refuelling safety,
- research concerning risk assessment methods applicable to hydrogen systems,
- European and international railway regulations and technical standards relevant to hydrogen applications,
- official reports and technical guidance documents providing relevant evidence concerning hydrogen railway safety.

Publications unrelated to hydrogen safety or railway applications, duplicate records, and sources lacking sufficient technical or regulatory relevance were excluded. Non-peer-reviewed sources were retained only where they provided primary regulatory information, official technical guidance, or project-specific information not available in peer-reviewed publications.

The selected material was analysed using a qualitative thematic synthesis. The information was classified into four main categories:

1. Hydrogen-related hazards and initiating events;
2. Railway-specific operational and infrastructural conditions;
3. Preventive and consequence-mitigation measures;
4. Applicable regulations, standards, and identified areas requiring further development.

The resulting information was subsequently compared across railway application areas, including rolling stock, refuelling facilities, maintenance facilities and the operating environment. Particular attention was given to the relationship between hydrogen-specific safety requirements and the existing railway safety management framework, including CSM RA and RAMS principles.

The purpose of this methodology was not to calculate numerical risk levels or establish a new quantitative risk assessment model but to provide a transparent and reproducible basis for identifying recurring hazards, evaluating the applicability of existing safety requirements and identifying European regulatory and technical gaps relevant to hydrogen railway applications.

## 3. Railway-Specific Hazards Associated with the Use of Hydrogen

Hydrogen is increasingly recognized as a promising zero-emission energy carrier for railway applications, offering significant potential to reduce greenhouse gas emissions and support the decarbonisation of rail transport. Although hydrogen has been safely produced, transported and utilized for several decades in industries such as chemical processing, aerospace, and, more recently, the automotive sector, its implementation in railway systems introduces a number of safety challenges that require careful consideration. The experience gained in these sectors provides a valuable foundation for developing safe hydrogen railway technologies. However, the operational characteristics of railway systems necessitate dedicated safety assessments and sector-specific regulatory solutions [1].

The principal hazards associated with hydrogen arise from its unique physicochemical properties. Hydrogen exhibits a wide flammability range (4–75% by volume in air), extremely low minimum ignition energy, high flame propagation velocity, and high diffusivity. Furthermore, because hydrogen molecules are very small, the gas can readily leak through joints, seals, and microscopic defects, and permeate through polymers, increasing the likelihood of undetected leaks. These characteristics distinguish hydrogen from conventional railway fuels, such as diesel, and require the implementation of dedicated engineering controls and operational procedures. While conventional fuels such as diesel and LPG are also flammable and hazardous, hydrogen is commonly stored under high pressure (e.g., 35 MPa) and exhibits distinct behaviour following an accidental release. Due to its low density, hydrogen rises and disperses rapidly in open, well-ventilated environments. However, in enclosed or poorly ventilated spaces, it may accumulate in upper areas and form flammable mixtures with air. In the event of a pressurised release, hydrogen may also form a high-velocity jet, which can ignite immediately or after mixing with air. The probability and consequences of ignition depend strongly on the release conditions, the surrounding environment, and the effectiveness of the implemented mitigation measures [9,10].

In railway applications, these hazards are further influenced by the location of hydrogen equipment, the movement and structural loading of rolling stock, the presence of passengers and railway personnel and the interaction between hydrogen installations and existing railway infrastructure. The principal railway-specific hazard areas are discussed below.

### *3.1. On-Board Hydrogen Storage and Loss of Containment*

The storage of hydrogen on railway vehicles is a major safety consideration because the required fuel capacity may be substantially greater than that used in hydrogen road vehicles, around 50 kg minimum for rail vehicles, whereas heavy-duty trucks would only require 80–100 kg of hydrogen. Depending on the vehicle design and operating range, hydrogen may be stored in high-pressure tanks installed on the roof or in other designated areas of the vehicle. The storage system includes not only pressure vessels, but also valves, pressure regulators, piping, connectors, sensors and associated protective devices. Failure or damage to any of these components may result in an uncontrolled hydrogen release [9,11–13].

Unlike stationary installations, on-board hydrogen systems are exposed to mechanical and environmental loads associated with railway operation. These include continuous vibration, dynamic loads during acceleration and braking, pressure cycling during refuelling and fuel consumption, temperature variations, and mechanical stresses resulting from vehicle operation. In addition, collision, derailment or other severe railway incidents may damage storage vessels, fuel lines or protective equipment. The integrity of the hydrogen installation must therefore be considered not only under normal operating conditions, but also under foreseeable abnormal and accident conditions.

The location of hydrogen storage equipment is particularly important. Roof-mounted installations may facilitate the dispersion of released hydrogen into the open atmosphere.

However, their design must account for the possibility of damage during collisions, interaction with overhead contact lines, and the consequences of a release near platforms, station structures, tunnels or other enclosed spaces. The arrangement of tanks and vent outlets should prevent hydrogen from entering passenger compartments, technical spaces or other areas in which accumulation and subsequent ignition could occur.

Material compatibility is another relevant issue. Hydrogen can cause embrittlement in certain metallic materials and may permeate through some non-metallic materials. Consequently, the selection of materials, joints and sealing technologies must take account of hydrogen compatibility, operating pressure, temperature and the expected service life of railway equipment. Inspection and maintenance arrangements should also consider the accessibility of storage components and the possibility of detecting degradation during the vehicle's operational lifetime [5,8–10].

### *3.2. Hydrogen Leakage, Accumulation and Ignition in Railway Environments*

An accidental hydrogen release may occur from storage vessels, fuel lines, valves, pressure regulators, connectors or auxiliary equipment. Depending on the release conditions and surrounding environment, hydrogen may disperse into the atmosphere, ignite immediately, causing micro-flames or a jet fire, or the release may continue. If the release continues, delayed ignition may occur, leading to a deflagration. In confined or semi-confined spaces, the accumulation of hydrogen may result in a flammable mixture and if ignition occurs, fire or explosion (deflagration or potentially a detonation). The effectiveness of natural or mechanical ventilation is therefore a critical factor in determining the potential consequences of a release [10,12,14,15].

Railway environments include a variety of locations in which hydrogen dispersion may be restricted. These include maintenance workshops, inspection halls, depots, enclosed service facilities, tunnels and covered station areas. In such locations, the geometry of the structure, roof configuration, ventilation openings and the position of hydrogen equipment may influence accumulation of hydrogen within flammability limits. Since hydrogen is lighter than air, it tends to rise and may accumulate near ceilings, roof structures or other upper parts of enclosed spaces. As a result, ventilation and detection systems must be designed with the specific geometry and use of each railway facility in mind.

The risk of hydrogen accumulation is particularly relevant during maintenance and inspection activities. Rolling stock may remain stationary inside workshops for extended periods, while maintenance personnel perform operations involving hydrogen installations. Activities such as opening connections, replacing components, testing systems or depressurizing and purging equipment may create conditions in which hydrogen is released. Safe working procedures should therefore include appropriate isolation of hydrogen systems, depressurisation and purging, gas monitoring, ventilation, and control of potential ignition sources.

Hydrogen leakage may also occur while a vehicle is stationary at a platform, during shunting or while operating inside a tunnel. In these situations, the consequences of a release may extend beyond the vehicle itself and affect passengers, railway employees, infrastructure, other trains and potentially the wider public. The assessment should consequently consider the possible migration of hydrogen into adjacent spaces, the availability of evacuation routes, and the ability of railway personnel and emergency services to identify and respond to a release.

With high-pressure hydrogen systems (35 MPa or 70 MPa rated pressure), there is the possibility of containment failure, i.e., the rupture of a component.

### 3.3. Hydrogen Refuelling and Interactions with Railway Infrastructure

Hydrogen refuelling is one of the most safety-critical activities in the operation of hydrogen-powered rolling stock. The process involves the transfer of hydrogen between the refuelling installation and the vehicle through high-pressure equipment and mechanical connections. Potential hazards include leakage during connection or disconnection, failure of hoses or couplings, incorrect operation of valves, overpressure, equipment malfunction and human error. The complete refuelling sequence should therefore be considered, including hydrogen delivery, stationary storage, compression where applicable, transfer to the vehicle, dispensing, disconnection and system depressurisation [4,5,16–19].

Railway refuelling facilities are often located within or adjacent to depots and other operational areas in which several activities take place simultaneously. Hydrogen refuelling may therefore interact with vehicle movements, shunting operations, maintenance work, passenger or freight operations, and the servicing of rolling stock using conventional fuels or battery-electric propulsion. These interfaces create additional organisational and operational challenges that are not necessarily present at dedicated hydrogen refuelling facilities designed for road vehicles.

Particular attention should be paid to the proximity of refuelling equipment to electrified railway tracks and overhead contact lines. Electrical equipment, switching operations and other potential ignition sources must be considered when determining the layout and operating arrangements of a refuelling facility. The assessment should also take into account the possibility of vehicle movement during refuelling, accidental disconnection of equipment, emergency shutdown and the safe isolation of the installation.

Environmental conditions may further influence refuelling safety. Wind direction and speed can affect the dispersion of released hydrogen, while temperature, precipitation and other weather conditions may influence equipment performance and personnel activities. The design and operation of railway refuelling facilities should therefore be based on site-specific assessments that consider the layout of the depot, surrounding buildings, railway infrastructure, access routes and the activities performed in the vicinity of the installation [16,17,19,20].

### 3.4. Hazards in Tunnels, Stations and Other Passenger-Accessible Areas

The operation of hydrogen-powered trains in tunnels and at stations requires particular consideration because these environments may restrict the dispersion of accidentally released hydrogen and complicate emergency response. The resulting consequences depend on the tunnel or station geometry, ventilation arrangements, the location of the release, train position and the availability of evacuation routes [12,14,21,22].

A hydrogen release in a tunnel may affect passengers, train crew, railway infrastructure and other trains operating in the same area. The presence of a train may further modify the local flow and dispersion conditions. In the event of fire or explosion, the confined geometry may influence the development of pressure effects, heat exposure and the movement of smoke or other combustion products from secondary fires. Consequently, the assessment of hydrogen-powered rolling stock intended for tunnel operation should consider credible leakage and ignition scenarios, the effectiveness of detection and ventilation systems, emergency communication, evacuation arrangements and access for rescue services.

At stations, the potential presence of passengers and other members of the public increases the importance of early detection, clear communication and effective emergency procedures. The assessment should consider whether hydrogen could migrate from the vehicle or its technical equipment towards passenger areas, station buildings or other enclosed spaces. It should also address the safe stopping and evacuation of a train following the detection of a hydrogen leak or a failure of the fuel system.

The requirements applicable to railway tunnels and rolling stock, including the relevant Technical Specifications for Interoperability, provide an important part of the railway safety framework [23–25]. However, hydrogen-specific scenarios should also be addressed through an application-specific risk assessment, since the presence of hydrogen storage and fuel systems introduces hazards that are not fully characterized by conventional rolling-stock fire safety provisions.

### 3.5. Maintenance, Inspection and Human Factors

Maintenance and inspection activities are essential for maintaining the integrity of hydrogen systems throughout the operational life of railway vehicles and refuelling infrastructure. They also create specific exposure scenarios for personnel working in close proximity to hydrogen storage vessels, pipelines, valves, sensors and other system components. Potential hazards include accidental damage during maintenance, incorrect isolation, incomplete depressurisation, residual hydrogen in the system, leakage following component replacement and the unintended introduction of ignition sources.

Safe maintenance requires procedures that define the conditions for isolating hydrogen installations, depressurising and purging relevant components, verifying the absence of hazardous hydrogen concentrations and controlling ignition sources. Hydrogen detection and adequate ventilation should be considered in workshops and other enclosed maintenance facilities. Inspection programmes should address the condition of pressure vessels, piping, connections, seals, protective devices and detection systems, taking into account the operating conditions and expected service life of the equipment.

Human factors are particularly important because hydrogen technologies require competencies that may differ from those traditionally associated with diesel-powered or electrically powered rolling stock. Drivers, maintenance personnel, refuelling operators, infrastructure managers and emergency responders should understand the specific properties of hydrogen, the operation of safety devices, the indications of a potential leak and the actions required in an emergency. Training and operating procedures should also address coordination between the different organisations involved in railway operations, infrastructure management, vehicle maintenance and fuel supply.

The management of hydrogen-related hazards should therefore extend beyond the technical design of individual components. It should include the organisation of work, allocation of responsibilities, personnel competence, maintenance documentation, inspection arrangements and emergency preparedness. These aspects should be considered throughout the system lifecycle in accordance with the railway RAMS approach and the applicable risk management framework [26–31].

### 3.6. Emergency Response and Consequences for Railway Operations

An emergency involving hydrogen-powered rolling stock or refuelling infrastructure may require actions that differ from those applied to conventional diesel-powered vehicles. Hydrogen is colourless and odourless, and its flame may be difficult to detect visually. Consequently, emergency responders should not rely exclusively on visual observation when determining whether a hydrogen release or fire is present. Appropriate gas detection, remote monitoring and information concerning the location and configuration of hydrogen equipment are important for supporting emergency decisions [10,11,20].

Emergency scenarios may include leakage without ignition, an immediately ignited release, delayed ignition, fire involving adjacent equipment, damage to a storage vessel following a collision or derailment and rupture of the containment system. The appropriate response depends on the nature and location of the event, the condition of the hydrogen system, the presence of passengers and railway personnel, and the accessibility of the site.

Procedures should define the conditions for stopping train movements, isolating hydrogen supplies, evacuating affected areas, establishing safety zones and coordinating the activities of railway personnel and emergency services.

Railway-specific emergency planning should also consider the location of the incident. Access to a train in a tunnel, on an elevated structure, at a remote section of track or within a depot may be difficult and may delay intervention. In addition, the presence of overhead contact lines and other electrical installations may impose additional requirements for the isolation of infrastructure before rescue or firefighting operations can begin. Emergency plans should therefore be developed in cooperation with railway undertakings, infrastructure managers, depot operators and local emergency services.

The consequences of a hydrogen-related incident may extend beyond direct injury, fire or damage to equipment. They may include disruption of railway operations, closure of infrastructure, evacuation of stations, interruption of passenger and freight services, and damage to adjacent railway assets. These operational consequences should be considered alongside the direct safety effects when defining risk control measures and emergency arrangements.

### *3.7. Summary of Railway-Specific Hazard Areas*

The identification of hydrogen-related hazards in railway applications requires consideration of both the physicochemical properties of hydrogen and the specific technical, operational and organisational conditions of railway systems. In particular, the potential consequences of hydrogen release depend on the location of the installation, the characteristics of the surrounding environment, the availability of ventilation and detection systems, and the presence of passengers and railway personnel. Table 1 provides an integrated qualitative analysis of the principal hazard areas identified in this review. It links potential initiating events and hazardous conditions with railway-specific exposure factors, possible consequences, relevant preventive and mitigative measures, and the applicable regulatory and standardisation framework. The table also identifies areas in which further technical evidence, railway-specific testing or regulatory development is required.

The analysis presented in Table 1 demonstrates that hydrogen safety in railway applications is a system-level issue that cannot be addressed solely through the selection and protection of individual hydrogen components. The identified hazards are strongly influenced by interactions between rolling stock, refuelling facilities, railway infrastructure, maintenance activities and operational procedures. Particular attention is required in enclosed or partially enclosed environments, such as tunnels, covered stations, depots and maintenance workshops, where hydrogen dispersion may be restricted, and emergency intervention may be more difficult. The analysis also highlights the importance of interfaces between hydrogen installations and electrified railway infrastructure, as well as the need for coordinated procedures involving railway undertakings, infrastructure managers, maintenance organisations and emergency services.

**Table 1.** Railway-specific hazard areas associated with hydrogen technologies.

| Hazard Area/ Scenario | Potential Initiating Events and Hazardous Conditions | Railway Specific Exposure Factors | Potential Consequences | Preventive and Mitigative Measures to Be Considered | Relevant Framework/Standards Cited in the Manuscript | Residual Issue/Evidence or Regulatory Gap |
|---|---|---|---|---|---|---|
| On-board storage and loss of containment | Mechanical damage or failure of a pressure vessel, valve, regulator, pipework or connection failure, material degradation, leakage following impact. | Continuous vibration, acceleration and braking loads, pressure and temperature cycling, collision or derailment, roof-mounted equipment, proximity to platforms, tunnels and overhead contact lines. | Hydrogen release, formation of a flammable cloud, jet fire following immediate ignition, delayed ignition or explosion in a confined/semi-confined space, damage to vehicle, infrastructure and rupture. | Hydrogen-compatible materials and seals, mechanical protection and appropriate tank location, pressure relief and isolation devices, leak detection, controlled vent routing, inspection and lifecycle maintenance, verification under representative railway loads. | CSM RA [26], EN 50126 series [27,28], rolling-stock TSIs [23–25], hydrogen/railway standardisation activities [32,33]. | Railway-specific qualification evidence is needed for vibration spectra, fatigue, pressure cycling, crash/derailment loads, vent discharge and long service life. The manuscript does not provide quantitative failure frequencies or validated railway-specific test results. |
| Hydrogen leakage from rolling stock during operation or stabling | Leakage from joints, seals, piping, valves, auxiliary equipment or damaged components, leakage after maintenance or component replacement. | Vehicle movement, roof or underframe installation, passenger presence, stopping at platforms, operation in tunnels and covered stations, adjacent technical spaces. | Local accumulation, ignition, fire or explosion, passenger/staff exposure, service disruption and infrastructure damage. | Leak-tight design, routine inspection, onboard gas detection where justified by the design, automatic or manual isolation, safe venting, operating instructions for leak alarms, maintenance and post-repair leak testing. | CSM RA [26], EN 50126 series [27,28], LOC&PAS TSI [23], SRT TSI [25], hydrogen safety literature [10–12,20,22]. | The manuscript identifies the scenarios but does not define performance requirements, sensor placement, alarm thresholds or validated dispersion criteria for different vehicle configurations and operating contexts. |
| Accumulation in depots, workshops and enclosed facilities | Release during stabling, inspection, maintenance, depressurisation, purging or equipment failure, inadequate or unavailable ventilation. | High roof spaces, pits and structural cavities, restricted natural ventilation, simultaneous maintenance tasks, personnel working close to hydrogen equipment, mixed-fuel depot activities. | Formation of a flammable hydrogen-air mixture, ignition, flash fire or explosion, injury to workers, damage to buildings and rolling stock. | Facility-specific ventilation assessment, hydrogen detection positioned according to release and dispersion analysis, alarm and shutdown logic, ignition-source control, safe isolation, depressurisation and purging, controlled access and work permits. | CSM RA [26], EN 50126 series [27,28], relevant hydrogen/refuelling standards cited in the manuscript [34–37]. | The article does not provide facility-specific ventilation or detector design criteria, nor validated modelling or experimental evidence for representative railway workshop geometries. |

**Table 1.** *Cont.*

| Hazard Area/ Scenario | Potential Initiating Events and Hazardous Conditions | Railway Specific Exposure Factors | Potential Consequences | Preventive and Mitigative Measures to Be Considered | Relevant Framework/Standards Cited in the Manuscript | Residual Issue/Evidence or Regulatory Gap |
|---|---|---|---|---|---|---|
| Hydrogen refuelling and fuel transfer | Hose or coupling failure, incorrect connection/disconnection, seal failure, overpressure, equipment malfunction, operator error, residual hydrogen during disconnection. | Refuelling within active depots, shunting and vehicle movements, concurrent maintenance, conventional-fuel operations and battery charging, nearby electrified tracks, weather exposure. | Uncontrolled release, jet fire or delayed ignition, personnel injury, damage to vehicles and facilities, interruption of depot operations. | Design and procedural controls for the complete transfer sequence, compatible couplings and hoses, pressure control and emergency shutdown, leak detection, safe separation and access arrangements, vehicle immobilisation, trained operators, emergency procedures. | CSM RA [26], EN 50126 series [27,28], hydrogen/refuelling standards and guidance cited in the manuscript [16–18,32–36]. | Railway depot-specific layouts, simultaneous operations, safety distances and interface requirements need application-specific assessment. The manuscript does not establish universal separation distances or quantitative risk levels. |
| Interaction with electrified railway infrastructure | Hydrogen release or vent discharge near electrical equipment, arcing or other potential ignition sources, inadequate coordination of isolation procedures. | Overhead contact lines, traction power equipment, switching and maintenance operations, constrained depot layouts, vehicle positioning during refuelling or maintenance. | Ignition of released hydrogen, fire or explosion, electrical hazards during emergency intervention, disruption of traction power and train movements. | Site layout and vent-direction assessment, identification and control of ignition sources, coordinated electrical isolation and hydrogen shutdown procedures, access control, interface risk assessment involving infrastructure and facility operators. | CSM RA [26], EN 50126 series [27,28], applicable railway TSIs [23–25], hydrogen technical standards cited in the manuscript [34–36]. | The manuscript identifies this interface but does not specify validated criteria for separation, vent orientation or coordinated isolation under different electrical and operational configurations. |
| Tunnel, covered-station and passenger-area operation | Leakage from a train or its hydrogen system, release following impact or component failure, delayed detection or ignition. | Restricted ventilation, tunnel and station geometry, train location, passenger density, evacuation distance, access limitations for rescue services, interaction with other trains. | Hydrogen accumulation, fire or explosion, passenger and crew injury, evacuation difficulties, damage to railway assets and prolonged closure. | Scenario-based assessment for each route and vehicle, consideration of ventilation and dispersion, detection and communication arrangements, emergency stopping and evacuation strategies, coordination with tunnel operators and rescue services. | SRT TSI [25], LOC&PAS TSI [23], CSM RA [26], hydrogen railway safety literature [12,14,21,22]. | The manuscript does not provide quantitative tunnel/station dispersion, overpressure or evacuation analyses. Representative scenarios and acceptance criteria require further research and application-specific evaluation. |

**Table 1.** *Cont.*

| Hazard Area/ Scenario | Potential Initiating Events and Hazardous Conditions | Railway Specific Exposure Factors | Potential Consequences | Preventive and Mitigative Measures to Be Considered | Relevant Framework/Standards Cited in the Manuscript | Residual Issue/Evidence or Regulatory Gap |
|---|---|---|---|---|---|---|
| Maintenance, inspection and human factors | Accidental damage, incorrect isolation, incomplete depressurisation or purging, residual hydrogen, incorrect reassembly, inadequate competence or communication. | Close personnel proximity, enclosed workshops, multiple contractors, varied maintenance tasks, differences between hydrogen, diesel and battery-electric procedures. | Leakage and accumulation, ignition during work, worker injury, latent defects, recurrence of failures after return to service. | Documented isolation, depressurisation and purging, gas testing, ventilation, ignition control, inspection and post-maintenance leak testing, competence-based training, clear responsibilities and work authorisation. | CSM RA [26], EN 50126 series [27,28], SMS requirements under Directive (EU) 2016/798 [38]. | The article does not define a detailed competence framework, task-specific maintenance safety requirements or a harmonised railway hydrogen inspection regime. |
| Emergency response and incident management | Leak without ignition, immediate or delayed ignition, jet fire, fire involving adjacent equipment, tank damage after collision/derailment, refuelling incident. | Flame may be difficult to see, incident may occur in a tunnel, station, depot or remote track, overhead line isolation, passenger evacuation, access and coordination constraints. | Delayed recognition, inappropriate intervention, escalation of fire or release, injury, secondary damage, prolonged interruption of railway operations. | Pre-planned incident scenarios, reliable gas/fire detection, access to system and tank information, isolation and shutdown instructions, evacuation and exclusion zones, coordination and joint exercises with emergency services. | Directive (EU) 2016/798 [38], CSM RA [26], EN 50126 series [27,28], SRT TSI [25], hydrogen safety literature [10,11,20]. | Railway-specific emergency tactics, responder information, detection performance and joint exercise protocols require validation. The manuscript does not quantify response-time effects or emergency scenario outcomes. |

Source: Authors' synthesis based on [10–12,14,16–18,20–25,32–38].

## 4. Regulatory and Standardization Framework for Hydrogen Applications in European Railways

The regulatory framework for hydrogen safety comprises multiple levels, including international regulations governing the transport of dangerous goods, European Union directives and regulations, national fire safety regulations and technical standards such as ISO and EN covering safety of refuelling infrastructure, storage systems, fittings, and hydrogen fuel quality [34–36]. Owing to hydrogen's wide flammability range, low ignition energy and high diffusivity, these regulations are intended to minimize the risk of catastrophic containment failure, accidental hydrogen release, mitigate explosion hazards, and establish requirements for safety distances, ventilation, and gas detection systems [37,39,40].

Since the inception of rail transport, safety has been regarded as one of its fundamental priorities, with railway regulations frequently serving as the basis for the development of the earliest legal frameworks. National railway systems, responsible for all aspects of rail operations within individual countries, played a key role in ensuring coherent and comprehensive protection against both safety and security risks. These systems established dedicated organizational structures, technical solutions, and regulatory frameworks for specific operational areas, which evolved with a certain degree of independence. Beginning in the 1990s, the railway sector in the European Union underwent significant restructuring. Traditional national railway organizations were divided into separate entities responsible for infrastructure management, including the allocation of train paths, and railway undertakings providing passenger and freight transport services using that infrastructure. This transformation created the need for a new, integrated approach to railway safety. Consequently, the principles of a modern railway safety management system were introduced through the EU Railway Safety Directive 2016/798 (RSD) [38], adopted by the European Parliament and the Council. The implementation of this Directive [38] also facilitated the development of interoperable services, i.e., those delivered by multiple infrastructure managers and railway undertakings.

In the European Union railway system the most important regulation which are applicable in the context of alternative power sources are EU Directives and Regulations such as the Technical Specifications for Interoperability (TSIs), the Fourth Railway Package and the Alternative Fuels Infrastructure Regulation (AFIR) Regulation EU 2023/1804 [41] which define the overarching requirements for railway systems and infrastructure. TSIs cover vehicles and fixed subsystems, but do not yet include hydrogen-specific provisions, leaving gaps for hydrogen technologies in railway systems. To fill these voids, the EU leverages standards developed by CEN, CENELEC, ISO and IEC. These standards provide detailed guidelines for hydrogen systems, such as refuelling interfaces, fuel cell integration and storage. Individual member states implement EU directives into national law and manage them. National Safety Agencies oversee vehicle approval, infrastructure permitting, and operational authorization. For hydrogen, this means that even where hydrogen isn't yet covered under TSIs, national authorities may require additional risk assessments, safety cases or ad hoc technical approvals, often informed by hydrogen-related standards like those from ISO/IEC/CEN. The relationship between European directives, national laws, TSIs, and hydrogen standards is complementary and adaptive, i.e., EU directives and TSIs frame the regulatory landscape, national laws operationalize it, hydrogen-specific standards fill the technical gaps, and industry-level guidance harmonizes the approval process. This multi-layered model ensures that hydrogen trains and infrastructure are authorized safely and consistently despite their innovative and technological complexity. Regarding the Technical Specifications for Interoperability, Directive (EU) 2016/797 [42] defines the subsystems, either structural or functional, forming part of the railway system of the European Union. These TSIs define the technical and operational standards which must be met by

each subsystem or part of a subsystem in order to meet the essential requirements and ensure the interoperability of the railway system of the European Union [43]. Introducing hydrogen propulsion in the case of railways in the EU requires therefore application of a specific approach.

### 4.1. Railway Transport Safety Domain

The EU Railway Safety Directive 2016/798 (RSD) [38] defines safety management rules for railway infrastructure companies and railway undertakings offering railway transport services, as well as for national railway safety authorities and railway accident investigation bodies. Those rules apply not only to new solutions but also to all existing technical and procedural solutions utilized for both operational and maintenance purposes. This directive defines common safety indicators (CSI), common safety targets (CST) and common safety methods (CSM), which together define the railway transport safety domain, ensuring and proving railway safety.

All railway infrastructure managers and undertakings providing transport services require both safety authorizations and safety certificates issued by national safety authorities as a prerequisite for railway activities. The basis for safety-related authorizations and certifications of the companies is formed by safety management systems comprising operational and maintenance procedures, as well as change management procedures, all linked with hazard logs individually defined and maintained by companies taking into account their specific circumstances and scope of activities. The RSD is therefore implemented through CSM on safety management systems, CSMs on safety authorization of the infrastructure managers and safety certification of the railway undertakings, as well as a CSM on safety management systems that are monitored both internally and by national safety authorities.

A separate set of rules are defined regarding safety indicators, targets and the way how national safety authorities and the European Union Agency for Railways are monitoring trends regarding changes in five types of individual risks and aggregated risk versus common safety targets. A dedicated, detailed approach is defined in Commission Decision 2009/460/EC [44] which links CSIs with CSTs using national reference values presently based on statistical data reflecting the previous six years of railway accidents and incidents in a certain country.

Last but not least, is an approach to technical, operational and organizational changes. This is defined by an implementing regulation on the common safety method for risk acceptance, CSM RA (Common Safety Method for Risk Evaluation and Assessment) [26]. This is directly applicable to introducing hydrogen propulsion in railway transport, especially as detailed technical requirements defined in so-called Technical Specifications for Interoperability TSIs [23–25] assigned to essential safety requirements are not sufficient, as hydrogen technology is rather new in this application. The CSM RA is supported by Railway Reliability, Availability, Maintainability and Safety (RAMS) standards [27–31], the concept of which is described below.

### 4.2. Safety Regulations in Railway in the Context of Use of Hydrogen Technologies

Passenger railway vehicles running on the interoperable TEN network shall fulfil the requirements of the LOC&PAS TSI [23], whereas freight rolling stock is covered by the requirements of the WAG TSI [24]. In addition, the SRT TSI [25] applies to rolling stock running in tunnels. However, the above documents do not contain requirements for alternative power sources, including hydrogen propulsion and associated installations, which are relatively new technical achievements. Therefore, this report is based on documents devoted to motor vehicles for on-road use.

The use of hydrogen in railway applications as an alternative to diesel fuel on non-electrified railway lines, like other alternative fuels, requires a consistent and harmonized railway safety framework. Such regulations are intended to ensure the safe production, storage, transportation, handling, and use of fuels and energy carriers within railway systems.

The existing regulations applicable to locomotives, passenger railway vehicles, other rolling stock, and railway infrastructure do not provide comprehensive, dedicated requirements for alternative fuels or energy carriers, including hydrogen propulsion systems and their associated installations, which represent relatively new technological solutions in the railway sector.

Currently, within the European Union (EU), interoperability of the railway system in terms of functional, technical, and organizational requirements, together with the provision of a consistent level of safety, is supported by the Technical Specifications for Interoperability (TSIs). Depending on the type of railway subsystem, the relevant areas include:

- Locomotives and Passenger Rolling Stock–Technical Specifications for Interoperability (TSI) [23],
- Rolling Stock–Freight Wagons–Technical Specifications for Interoperability (TSI) [24],
- Safety in Railway Tunnels–Technical Specifications for Interoperability (TSI) [25].

Requirements concerning the safety of passengers and train crew in relation to fire protection are primarily addressed by the EN 45545 series of European standards, consisting of Parts 1–7 [45]. However, the current provisions do not comprehensively cover alternative fuels or energy carriers and do not include specific requirements for hydrogen-powered railway vehicles and their associated systems. This limitation is largely due to the fact that the standard series was developed before alternative propulsion technologies were introduced into railway rolling stock. The ongoing revision of EN 45545-5 [45], carried out by a dedicated CEN Working Group, is intended to address emerging power supply and propulsion technologies, including hydrogen [6].

At the European level, one of the principal legal instruments establishing the overall safety framework for railway transport is Directive (EU) 2016/798 of the European Parliament and of the Council on railway safety (RSD) [38]. The Directive establishes safety requirements applicable to the railway system as a whole, including the safe management of railway infrastructure and operations, as well as the interactions between railway undertakings, infrastructure managers, and other actors involved in the European railway system. This Directive defines, among other things:

- Common Safety Targets (CST) defined as the minimum safety levels that are to be reached by the system as a whole, and where feasible, by different parts of the EU railway system, expressed in risk acceptance criteria.
- Common Safety Methods (CSM) defined as the methods describing the assessment of safety levels and achievement of safety targets and compliance with other safety requirements.
- Safety Management Systems (SMS) defined as the organisation, arrangements and procedures established by an infrastructure manager and/or a railway undertaking to ensure the safe management of its operations.
- National Safety Authorities (NSA) defined as the national bodies entrusted with the tasks regarding railway safety in accordance with the Directive or bodies entrusted by several Member States with those tasks in order to ensure a unified safety regime for specialised cross-border infrastructures.

Directive (EU) 2016/798 [38] defines the concepts of an accident, serious accident, and incident within its scope, but does not provide an explicit definition of safety itself.

To identify such a definition, it is therefore necessary to refer to more specific regulatory instruments, namely the documents establishing the Common Safety Methods (CSMs). Six such regulations are currently in force, defining six complementary Common Safety Methods applicable to different aspects of railway safety. One of these is Commission Implementing Regulation (EU) No 402/2013 on the common safety method for risk evaluation and assessment and repealing Regulation (EC) No 352/2009 [26], is specifically applicable to the introduction of technical, operational, and/or organizational changes to the railway system or parts thereof. Consequently, the application of this method is required when introducing new technologies into railway transport, where such changes fall within its scope. Regulation (EU) No 402/2013 [26] establishes the Common Safety Method for risk evaluation and assessment and defines "safety" as the absence of unacceptable risk. Based on the above regulation, the following terms are defined:

- Risk—meaning the frequency of occurrence of accidents and incidents resulting in harm (caused by a hazard) and the degree of severity of that harm;
- Risk analysis—meaning systematic use of all available information to identify hazards and to estimate the risk;
- Risk evaluation—meaning a procedure based on the risk analysis to determine whether an acceptable level of risk has been achieved;
- Risk assessment—meaning the overall process comprising a risk analysis and a risk evaluation;
- Risk management—meaning the systematic application of management policies, procedures and practices to the tasks of analysing, evaluating and controlling risks;
- Risk acceptance criteria—meaning the terms of reference by which the acceptability of a specific risk is assessed; these criteria are used to determine that the level of a risk is sufficiently low that it is not necessary to take any immediate action to reduce it further;
- Risk acceptance principle—meaning the rules used in order to arrive at the conclusion whether or not the risk related to one or more specific hazards is acceptable;
- Risk estimation—meaning the process used to produce a measure of the level of risks being analysed, consisting of the following steps: estimation of frequency, consequence analysis and their integration;
- Hazard—meaning a condition that could lead to an accident;
- Hazard record—meaning the document in which identified hazards, their related measures, their origin and the reference to the organisation which has to manage them are recorded and referenced;
- Safety requirements—meaning the safety characteristics (qualitative or quantitative) of a system and its operation (including operational rules) and maintenance necessary in order to meet legal or company safety targets;
- Safety measures—meaning a set of actions either reducing the frequency of occurrence of a hazard or mitigating its consequences in order to achieve and/or maintain an acceptable level of risk.

### *4.3. Procedures for Hazard Identification and Risk Acceptance for Hydrogen in Railway Applications*

To minimize the risks associated with the introduction of hydrogen technologies into railway transport, particularly hydrogen refuelling stations and hydrogen-powered rolling stock, it is necessary to establish a systematic risk assessment methodology that enables the identification of appropriate risk control measures and the definition of applicable safety requirements [22,46]. The implementation of hydrogen technologies should incorporate measures to reduce both the likelihood and consequences of fire and explosion scenarios, including thermal radiation and blast overpressure, to levels acceptable under the applicable

safety criteria [22,46]. Comprehensive risk assessment is particularly important during the deployment of hydrogen technologies in railway applications, where hydrogen-specific hazards must be evaluated in the context of railway operating conditions and infrastructure. Although dedicated railway standards for on-board hydrogen and fuel-cell systems have been published, further assessment may be needed to address the full range of refuelling, depot operation, infrastructure-integration, and emergency response scenarios [22,32,46].

Where appropriate, selected risks may be addressed through the application of relevant industrial or automotive regulatory requirements combined with applicable railway standards [27,28]. Such an approach should take into account the specific operating, environmental, and functional conditions of railway applications, including any necessary deviations from the requirements originally developed for other sectors [22,23]. Hazards that cannot be adequately controlled through existing requirements must be addressed through additional safety measures, with appropriate evidence demonstrating that the resulting residual risks have been reduced to an acceptable level. Even where industrial requirements are applied in conjunction with railway standards, a systematic demonstration of safety is required to confirm that no unacceptable risks remain [27,28].

The introduction of hydrogen-powered rolling stock and the associated hydrogen refuelling infrastructure should therefore be regarded, where applicable, as a significant technical change with potential implications for railway safety. Such changes require a structured assessment and approval process in accordance with the Common Safety Method for Risk Evaluation and Assessment (CSM RA) [26]. The CSM RA provides the principal framework for assessing changes to the railway system and applies when technical, operational, or organisational modifications are proposed that may affect safety. Consequently, the introduction of hydrogen fuel cell rolling stock or an interoperable hydrogen refuelling station should be assessed according to the principles and procedures established by the CSM RA.

The deployment of hydrogen technologies also introduces technology-specific hazards that require continuous assessment throughout the system lifecycle to ensure an adequate level of safety and reliability. These hazards may affect not only human life, health, and property, but also the overall safety and continuity of railway operations. The deployment of hydrogen technologies introduces technology-specific hazards that require systematic assessment throughout the entire system lifecycle. These hazards may affect human life, health and property, as well as the safety and continuity of railway operations. The safety of hydrogen-powered railway applications therefore needs to be demonstrated in relation to the specific technical configuration, infrastructure, operating conditions and maintenance arrangements of each application. This requires a clearly defined safety framework addressing the conditions under which hydrogen-powered rolling stock and associated infrastructure can be designed, introduced, operated, maintained and eventually decommissioned [21].

The introduction of hydrogen-powered rolling stock and hydrogen refuelling stations may consequently constitute a significant safety-related change and should be assessed against the criteria specified in the CSM RA Regulation. Technical, operational, and organisational changes affecting railway safety are evaluated with respect to their significance using six established criteria. This assessment is independent of whether the proposed change is expected to improve or potentially reduce the existing level of safety [26]. In the context of hydrogen railway applications, at least four of these criteria may be particularly relevant: the potential consequences of failure, the innovative character of the proposed solution, the complexity of the change, and the inability to ensure its technical reversibility. The remaining criteria concern the ability to monitor the system throughout its lifecycle and the cumulative effect of the proposed change when considered together with previous changes that were individually assessed as non-significant [47].

Given the physical and chemical properties of hydrogen, including its high flammability and high energy content, an accidental release or loss of containment may result in severe or potentially catastrophic consequences. Hydrogen-based solutions introduced into railway applications should therefore be regarded as innovative technologies, particularly under the current conditions of railway operation, and their implementation requires the development of new competencies, procedures, and technical tools. The associated technical changes may involve the introduction of technologies that differ from those traditionally used in railway systems, including high-pressure storage vessels, hydrogen gas installations, hydrogen detection and monitoring systems, pressure and temperature sensors, and communication systems for transmitting safety-critical and, where applicable, operational or billing-related data [22].

The organisational and operational implications of hydrogen technology deployment should also be considered. Personnel involved in the operation, maintenance, inspection and emergency response of hydrogen systems require appropriate knowledge, skills and competencies. Furthermore, the reversibility of the proposed change requires specific consideration. For example, the eventual decommissioning or withdrawal of hydrogen-powered traction vehicles may involve not only economic considerations but also safety, organisational and logistical constraints. These may include maintaining an adequate availability of traction vehicles and ensuring reasonable vehicle turnaround times during the transition to alternative traction technologies.

The introduction of hydrogen-powered rolling stock and hydrogen refuelling infrastructure should therefore be accompanied by a comprehensive, application-specific risk assessment and the identification and implementation of appropriate risk control measures. The assessment should provide documented evidence that the identified risks have been reduced to an acceptable level in accordance with the applicable safety requirements and that the effectiveness of the adopted measures is appropriately verified. Hydrogen-based railway applications may require treatment as safety-significant changes, depending on their technical and operational characteristics. Where required, an appropriate safety case should be developed to document the safety arguments and supporting evidence. Railway standards addressing Reliability, Availability, Maintainability and Safety (RAMS) can provide a relevant framework for this process [27–31].

In accordance with the RAMS approach, safety-related analyses, decisions and evidence are developed and documented throughout the complete system lifecycle, beginning with the initial concept and extending through design, implementation, verification, validation, acceptance, operation, maintenance and final decommissioning. This lifecycle-based approach is particularly relevant to hydrogen-powered rolling stock and refuelling infrastructure for which safety risks may evolve as the system progresses through different life cycle phases.

The RAMS standards define twelve lifecycle phases for railway systems. These phases are commonly represented using a “V-model”, which illustrates the sequential development and corresponding verification and validation activities throughout the system lifecycle. The model covers the progression from the initial definition of system requirements and concept development through design, implementation, integration, testing, acceptance, operation, maintenance and eventual decommissioning. The lifecycle structure specified in EN 50126-1:2017 [27] is presented in Figure 3.

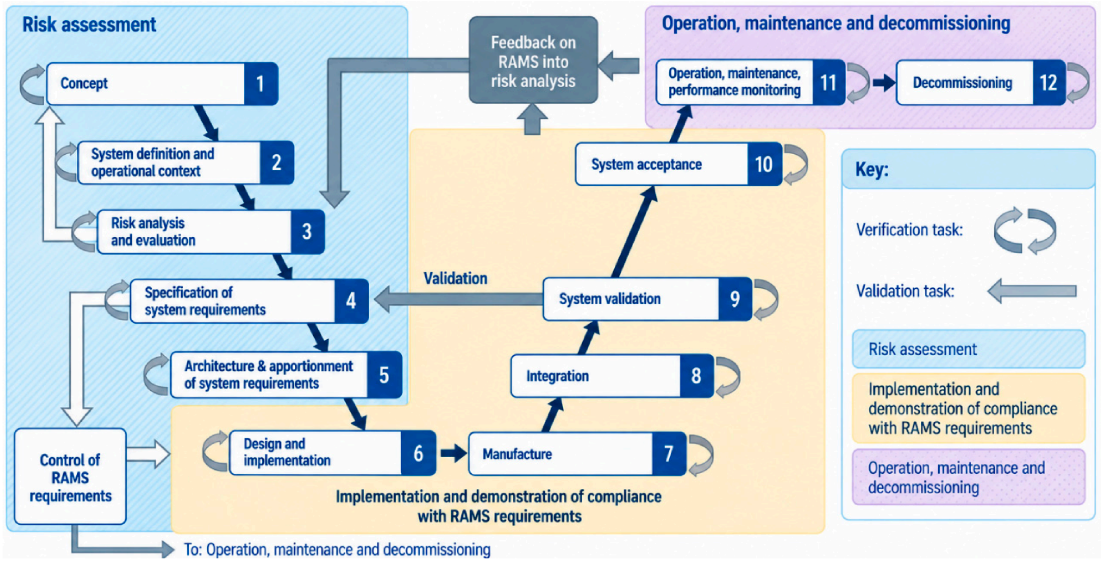



**Figure 3.** Life cycle phases of a system/device/component according to RAMS standards. Source: Authors' own elaboration based on EN 50126-1:2017 [27].

Reliability, Availability, Maintainability (RAM) and Safety-related activities shall be specified for each phase of the project. Several fundamental aspects must be considered in this context. The RAMS standards provide a framework for developing safety cases for generic solution types. However, they also require the preparation of safety cases for specific applications. Accordingly, a particular type of hydrogen refuelling station shall be covered by a safety case prepared by its manufacturer. In addition, a separate safety case shall be developed for the deployment of the station at a designated site, considering the specific conditions and characteristics of the location concerned.

The RAMS standards stipulate that safety analyses account for risks associated with both random failures and human errors. Consequently, safety cases should address not only the technical characteristics of the proposed solution but also production quality assurance and supervisory procedures, including the competence of personnel involved in activities such as the manufacture and installation of hydrogen refuelling stations for rolling stock. This approach is justified by the fact that particular failure modes may result, depending on external conditions or their interaction with other failures, in either reduced operational performance, such as the unavailability of a refuelling station, or compromised safety, potentially leading to unacceptable levels of risk. The RAMS standards establish different safety integrity levels and classify methods for achieving the required levels of reliability, availability, maintainability, and safety as recommended, strongly recommended, not recommended or not applicable. Nevertheless, these recommendations were not specifically developed with hydrogen-powered rolling stock and its refuelling infrastructure in mind.

Considering these three premises, the methodology specified in the RAMS standards can be applied to the following areas:

- The development of a hazard record, including anticipated risk levels expressed in terms of frequency and severity, together with proposed risk acceptance criteria;
- The establishment of a framework for a type-specific generic application safety case for hydrogen refuelling stations;
- The definition of requirements and procedures for preparing complete generic application safety cases for individual types of hydrogen refuelling stations;
- The specification of requirements and procedures for developing specific application safety cases for individual hydrogen refuelling stations deployed at designated locations.

Under Commission Implementing Regulation (EU) No 402/2013, as amended, the proposer is responsible for determining whether a proposed change to the railway system has an impact on safety and, where it does, whether the change is significant. If the change is classified as significant, the proposer is required to apply the common safety method for risk evaluation and assessment (CSM RA) [26]. This process includes the identification and evaluation of hazards, the definition of appropriate safety measures and safety requirements, and the demonstration that these requirements have been fulfilled. The suitability of the application of the risk management process and its results must be independently assessed by an assessment body meeting the competence and independence criteria.

### 4.4. Risk-Based Approach to Hydrogen Safety in Railway Applications

The railway-specific approach described above is undoubtedly complex and demanding. However, it represents a well-established practice that has been applied for approximately twenty-five years with satisfactory results. At the beginning of the 21st century, the national railway systems of European Union Member States were reorganized into independent infrastructure managers, railway undertakings, national safety authorities, and investigation bodies, as described above. This organizational transformation introduced additional risks, particularly due to the presence of multiple independent passenger and freight operators using the same railway infrastructure while applying their own detailed rules and operational procedures. Experience from the initial years demonstrated that maintaining safety across such a complex organizational structure represented a significant challenge and that safe interoperability between all organizations involved in the railway sector was essential. Consequently, the first European railway safety directive was adopted in 2004, followed by the introduction of the first Common Safety Method for Risk Assessment (CSM RA) in 2009.

The European Union Agency for Railways publishes annual reports on railway transport safety, addressing, among other aspects, safety targets and risk acceptance. These reports provide an overview of railway safety trends at the system level. The Common Safety Method for Risk Evaluation and Assessment (CSM RA) provides a structured approach to assessing the safety implications of technical, operational and organisational changes. However, the application of this methodology alone cannot be regarded as evidence that the overall railway safety level has been maintained. Railway safety performance is influenced by multiple interrelated factors, including technical developments, operational practices, safety management arrangements, regulatory oversight and external conditions.

The introduction of hydrogen propulsion requires the implementation of hydrogen refuelling systems that must meet stringent safety requirements. The lack of railway-specific codes of practice and reference systems for hydrogen technologies necessitates the use of codes and references developed for other industrial sectors, combined with railway-specific safety-related change management procedures. Although this approach presents significant challenges, it provides a practical and reasonable basis for safety assessment, particularly when the specific characteristics of railway transport, including train mass, operating speeds, and braking distances, and their influence on the potential severity of accidents are taken into account.

### 4.5. International Standards

International standardization is of fundamental importance for facilitating the transition of railway rolling stock from diesel propulsion to hydrogen-based power systems. Over the past 25 years, substantial international efforts have been devoted to establishing regulations and standards for both light- and heavy-duty road vehicles within the automotive industry, including those presented in [48–50]. These standards must now be adapted

to account for the specific operating and environmental conditions encountered in railway applications, including the following factors:

- the amount of hydrogen stored may vary from approximately 50 kg to several hundred kilograms,
- railway applications are expected to require significantly longer service lives than those typically considered in the automotive sector,
- hydrogen storage systems in railway vehicles will be subjected to pressure cycling patterns that differ from those encountered in road vehicles,
- vibration requirements will need to reflect the specific vibration spectra characteristic of railway applications,
- the systems will have to withstand accident loads that differ from those considered for automotive vehicles,
- certain testing criteria may also require modification, including, for instance, permissible hydrogen permeation or leakage rates,
- the use of a larger number of pressure relief device vents may be necessary,
- higher hydrogen refuelling rates may potentially be required.

IEC TC9 is cooperating with IEC TC105 in the development of standards specifically addressing railway applications [32,33]. However, these activities should also draw upon the knowledge and experience of the road vehicle supply chain represented by ISO TC197, which has been responsible for developing standards concerning hydrogen storage systems and refuelling technologies in the automotive sector. Establishing joint working groups that combine expertise from both industries is important to ensure that the transfer or adaptation of existing requirements does not introduce errors or overlook safety-related aspects.

## 5. Conclusions

The implementation of hydrogen technologies in railway transport offers an opportunity to reduce the environmental impact of rail operations, particularly on non-electrified lines. However, the environmental benefits depend on the hydrogen production pathway and the associated energy supply chain. Therefore, the absence of emissions at the vehicle level should not be interpreted as zero greenhouse gas emissions over the entire hydrogen life cycle. In parallel with the potential environmental benefits, the introduction of hydrogen-powered rolling stock and refuelling infrastructure creates specific safety challenges that must be addressed within the established railway safety management framework.

This review examined the relationship between hydrogen-related hazards, railway operating conditions, risk management procedures, and the applicable European regulatory and standardisation framework. The qualitative synthesis indicates that the principal safety challenges arise not only from the physicochemical properties of hydrogen but also from its interaction with railway vehicles, infrastructure, operational processes, and the organisations responsible for railway safety. The identified hazard areas include on-board hydrogen storage and loss of containment, leakage during refuelling, hydrogen accumulation in enclosed or partially enclosed spaces, ignition, maintenance activities, interactions with electrified infrastructure, and emergency response. These hazards may be further influenced by railway-specific conditions, including vehicle vibration, dynamic and crash loads, pressure cycling, restricted ventilation in tunnels and maintenance facilities, passenger presence, and the simultaneous performance of different activities in depots.

The analysis also indicates that the existing European railway safety framework provides a general basis for managing risks associated with the introduction of hydrogen technologies. In particular, Directive (EU) 2016/798, the Common Safety Method for Risk Evaluation and Assessment (CSM RA), and the RAMS principles established in the EN 50126 series provide relevant procedures for identifying hazards, assessing safety implica-

tions, defining safety requirements, and demonstrating that risks have been controlled to an acceptable level. Nevertheless, the application of these general railway procedures does not eliminate the need for hydrogen-specific technical evidence. The existing railway requirements and standards do not address all interfaces between hydrogen installations, rolling stock, refuelling facilities, maintenance activities, and railway operating environments in sufficient detail. Consequently, the assessment of each proposed application should consider its technical configuration, location, operating conditions, maintenance arrangements, and emergency response provisions.

The present study has limitations that should be considered when interpreting its findings. It adopts a structured narrative review and qualitative thematic synthesis rather than a systematic review or a quantitative risk assessment. The hazard classification and regulatory mapping are intended to support the identification of relevant safety issues and areas requiring further investigation; they do not provide numerical estimates of accident frequency, consequence severity, or individual and societal risk. Furthermore, the availability of railway-specific operational data and validated experimental evidence remains limited for some hydrogen-related scenarios. Therefore, the identified hazards and recommendations should not be treated as a substitute for a detailed, application-specific risk assessment carried out for a particular vehicle, refuelling facility, or railway location.

The findings of this review lead to six practical priorities for the further development and safe deployment of hydrogen technologies in railway systems:

- Quantitative assessment of representative accident scenarios. Further research should prioritise quantitative analysis of hydrogen releases, dispersion, accumulation, ignition, jet fires, and explosion consequences in railway-specific environments. Particular attention should be given to tunnels, covered stations, workshops, inspection halls, depots, and refuelling areas. The selection of scenarios and modelling assumptions should reflect the actual configuration of the vehicle or facility, ventilation conditions, release characteristics, and the presence of passengers and railway personnel.
- Development of railway-specific testing and verification procedures. Dedicated testing should address the behaviour and integrity of on-board hydrogen storage systems, pipelines, valves, connections, and protective equipment under railway operating conditions. Relevant factors include vibration, dynamic loading, pressure and temperature cycling, fatigue, and the mechanical loads associated with collision or derailment. Verification should also consider the compatibility of hydrogen installations with existing vehicle structures and electrified railway infrastructure.
- Improvement of safety requirements for refuelling and maintenance facilities. The design and operation of railway refuelling facilities should be supported by application-specific assessments covering equipment failure, leakage, overpressure, ventilation, gas detection, ignition sources, vehicle movements, and simultaneous depot activities. Maintenance procedures should clearly address isolation, depressurisation, purging, inspection, and the verification of safe conditions before work begins. Personnel competence and coordination between railway undertakings, infrastructure managers, facility operators, and maintenance organisations are also essential.
- Integration of hydrogen-specific safety evidence into railway approval and safety management processes. Evidence generated during design, testing, risk assessment, and operational validation should be incorporated into the relevant safety documentation for rolling stock and infrastructure. Where the introduction of hydrogen technology constitutes a significant change within the scope of the CSM RA, the assessment should identify hazards, define appropriate safety measures and acceptance criteria, allocate responsibilities, and establish safety-related application conditions. The resulting re-

quirements should be reflected in operating instructions, maintenance documentation, emergency plans, and the safety management systems of the organisations concerned.

- Another important issue for future research is the potential interaction between hydrogen and other combustible substances present in railway environments. Recent experimental studies on petrol vapour–hydrogen mixtures indicate that explosion characteristics may be affected by multiple interacting factors [51]. Although these findings are not directly transferable to railway applications, they highlight the need to investigate mixed-fuel release and ignition scenarios, particularly in depots, maintenance facilities and refuelling areas where hydrogen systems may operate in proximity to conventional fuels. Future research should therefore consider the influence of mixed combustible atmospheres on explosion hazards and develop railway-specific assessment methods supported by experimental validation
- Further development and harmonisation of standards and emergency response arrangements. Cooperation between the railway, hydrogen, and automotive standardisation communities should be continued to address requirements that are not yet sufficiently adapted to railway applications. Priority areas include hydrogen detection, ventilation, fire protection, storage-system integrity, refuelling interfaces, and the management of incidents in tunnels and enclosed railway facilities. Emergency response arrangements should also be developed and tested jointly with relevant railway organisations and rescue services, taking into account the specific characteristics of hydrogen fires and the operational constraints of railway infrastructure.

In conclusion, the safe implementation of hydrogen technologies in railway transport requires the combination of hydrogen-specific engineering safeguards with the established principles of European railway safety management. The CSM RA and RAMS frameworks provide an appropriate basis for organising this process, while further technical research, railway-specific testing, and standardisation are needed to address the remaining gaps. The practical value of the approach presented in this review lies in linking hydrogen-related hazards with railway operating conditions and the applicable safety framework, thereby supporting more consistent hazard identification, the definition of safety requirements, and the preparation of application-specific safety assessments.

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## References

1. European Commission. *The European Green Deal*; COM(2019) 640 Final; European Commission: Brussels, Belgium, 2019.

2. Wojtkiewicz, M. Emisje z Transportu: Czas na Zmianę Paradygmatu [Transport Emissions: Time for a Paradigm Shift]. Available online: https://www.teraz-srodowisko.pl/aktualnosci/emisje-transport-kolejowy-drogowy-lotniczy-GHG-11142.html (accessed on 5 November 2026).
3. Radziszewska-Wolińska, J.; Kaźmierczak, A.; Milczarek, D. European Approach to Fire Safety in Rolling Stock. *Appl. Sci.* **2025**, *15*, 12671. [CrossRef]
4. Zhao, A.P.; Li, S.; Xie, D.; Wang, Y.; Li, Z.; Hu, P.J.-H.; Zhang, Q. Hydrogen as the nexus of future sustainable transport and energy systems. *Nat. Rev. Electr. Eng.* **2025**, *2*, 447–466. [CrossRef]
5. Xu, Z.; Zhao, N.; Hillmansen, S.; Roberts, C.; Yan, Y. Techno-Economic Analysis of Hydrogen Storage Technologies for Railway Engineering: A Review. *Energies* **2022**, *15*, 6467. [CrossRef]
6. Radziszewska-Wolińska, J.M. *Alternative Power in Rolling Stock, Modern Trends in Fire Protection of Railway Rolling Stock*; Instytut Kolejnictwa: Warsaw, Poland, 2024; pp. 129–143.
7. Girard, S.; Hernandez, M.; Jimenez, I.; Brinkerhoff, J.R. Qualitative risk assessment for hydrogen and battery locomotives. *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit.* **2025**, *239*, 740–750. [CrossRef]
8. Sun, Y.; Anwar, M.; Hassan, N.M.S.; Spiryagin, M.; Cole, C. A Review of Hydrogen Technologies and Engineering Solutions for Railway Vehicle Design and Operations. *Railw. Eng. Sci.* **2021**, *29*, 212–232. [CrossRef]
9. Sánchez, A.L.; Williams, F.A. Recent Advances in Understanding of Flammability Characteristics of Hydrogen. *Prog. Energy Combust. Sci.* **2014**, *41*, 1–55. [CrossRef]
10. Yang, F.; Wang, T.; Deng, X.; Dang, J.; Huang, Z.; Hu, S.; Li, Y.; Ouyang, M. Review on Hydrogen Safety Issues: Incident Statistics, Hydrogen Diffusion, and Detonation Process. *Int. J. Hydrogen Energy* **2021**, *46*, 31467–31488. [CrossRef]
11. Qanbar, M.W.; Hong, Z. A Review of Hydrogen Leak Detection Regulations and Technologies. *Energies* **2024**, *17*, 4059. [CrossRef]
12. Sun, X.; Yang, J.; Wang, J.; Chen, X.; Shi, J. Analytical Model of Critical Ventilation Flow Rate for Accidental Hydrogen Leakage in a Confined Space. *Energies* **2023**, *16*, 6864. [CrossRef]
13. Groth, K.M.; Li, R.; Al-Douri, A.; Ustolin, F.; Yang, R. Hydrogen Safety for Production, Infrastructures, Vehicles and Aviation. *Nat. Rev. Clean Technol.* **2026**, *2*, 476–491. [CrossRef]
14. Brzezińska, D. Hydrogen Dispersion and Ventilation Effects in Enclosures under Different Release Conditions. *Energies* **2021**, *14*, 4029. [CrossRef]
15. Calabrese, M.; Portarapillo, M.; Di Nardo, A.; Venezia, V.; Turco, M.; Luciani, G.; Di Benedetto, A. Hydrogen Safety Challenges: A Comprehensive Review on Production, Storage, Transport, Utilization, and CFD-Based Consequence and Risk Assessment. *Energies* **2024**, *17*, 1350. [CrossRef]
16. Kim, Y.; Han, S.; Song, H.; Jung, S. Risk Assessment of an Off-Site Hydrogen Refueling Station: A Hybrid IEC 61511-CCPS LOPA Framework. *Energies* **2025**, *18*, 6242. [CrossRef]
17. Rusin, A.; Stolecka-Antczak, K.; Kosman, W.; Rusin, K. The Impact of the Configuration of a Hydrogen Refueling Station on Risk Level. *Energies* **2024**, *17*, 5504. [CrossRef]
18. Nekhwevha, R.; Madyira, D.M.; Gqibani, S.L. Analysis of Equipment Failures as a Contributor to Hydrogen Refuelling Stations Incidents. *Hydrogen* **2025**, *6*, 79. [CrossRef]
19. Badia, E.; Navajas, J.; Sala, R.; Paltrinieri, N.; Sato, H. Analysis of Hydrogen Value Chain Events: Implications for Hydrogen Refueling Stations' Safety. *Safety* **2024**, *10*, 44. [CrossRef]
20. Federal Railroad Administration. *Study of Hydrogen Fuel Cell Technology for Rail Propulsion and Review of Relevant Industry Standards*; Report No. DOT/FRA/ORD-21/20; U.S. Department of Transportation: Washington, DC, USA, 2021.
21. Xu, L.; Li, Y.; Zhang, W.; Ma, T.; Jing, X. Safety Analysis of Hydrogen-Powered Train in Different Application Scenarios: A Review. *Energies* **2025**, *18*, 1743. [CrossRef]
22. Sun, Y.-Q. Explosions of Hydrogen Storages and the Safety Considerations in Hydrogen-Powered Railway Applications—A Review. *Hydrogen* **2024**, *5*, 901–918. [CrossRef]
23. European Union. *TSI LOC&PAS-COMMISSION REGULATION (EU) No 1302/2014, of 18 November 2014 Concerning a Technical Specification for Interoperability Relating to the 'Rolling Stock-Locomotives and Passenger Rolling Stock' Subsystem of the Rail System in the European Union*; European Union: Brussels, Belgium, 2014.
24. European Union. *TSI WAG-COMMISSION REGULATION (EU) No 321/2013, of 13 March 2013, Concerning the Technical Specification for Interoperability Relating to the Subsystem 'Rolling Stock-Freight Wagons' of the Rail System in The European Union and Repealing Decision 2006/861/EC*; European Union: Brussels, Belgium, 2013.
25. European Union. *TSI SRT-COMMISSION REGULATION (EU) No 1303/2014 of 18 November 2014 Concerning the Technical Specification for Interoperability Relating to 'Safety in Railway Tunnels' of the Rail System of the European Union*; European Union: Brussels, Belgium, 2014.
26. European Union. *Commission Implementing Regulation (EU) No 402/2013 of 30 April 2013 on the Common Safety Method for Risk Evaluation and Assessment and Repealing Regulation (EC) No 352/2009, as Amended by Commission Implementing Regulation (EU) 2015/1136 of 13 July 2015*; European Union: Brussels, Belgium, 2013.

27. *EN 50126-1:2017*; Railway Applications—The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS)—Part 1: Generic RAMS Process. European Committee for Electrotechnical Standardization: Brussels, Belgium, 2017.
28. *EN 50126-2:2017*; Railway Applications—The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS)—Part 2: Systems Approach to Safety. European Committee for Electrotechnical Standardization: Brussels, Belgium, 2017.
29. *EN 50128:2011*; Railway Applications. Communication, Signalling and Processing Systems. Software for Railway Control and Protection Systems. European Committee for Electrotechnical Standardization: Brussels, Belgium, 2011.
30. *EN 50129:2026*; Railway Applications—Communication, Signalling and Processing Systems—Safety Related Electronic Systems for Signalling. European Committee for Electrotechnical Standardization: Brussels, Belgium, 2026.
31. *EN 50159:2026*; Railway Applications—Communication, Signalling and Processing Systems—Safety-Related Communication in Transmission Systems. European Committee for Electrotechnical Standardization: Brussels, Belgium, 2026.
32. *IEC 63341-2:2025*; Railway Applications—Hydrogen and Fuel Cell Systems for Rolling Stock—Part 2: Hydrogen Fuel System. IEC: Geneva, Switzerland, 2025.
33. *IEC 63341-1*; Railway Applications—Hydrogen and Fuel Cell Systems for Rolling Stock—Part 1: Fuel Cell System. IEC: Geneva, Switzerland, 2025.
34. European Agreement Concerning the International Carriage of Dangerous Goods by Road. 2023. Available online: https://www.un-ilibrary.org/content/periodicals/24118613 (accessed on 6 October 2026).
35. Melaina, M.; Penev, M. *Hydrogen Station Cost Estimates: Comparing Hydrogen Station Cost Calculator Results with Other Recent Estimates*; National Renewable Energy Laboratory: Golden, CO, USA, 2013.
36. National Fire Protection Association. *NFPA 2: Hydrogen Technologies Code*; National Fire Protection Association: Quincy, MA, USA, 2023. Available online: https://www.nfpa.org/codes-and-standards/nfpa-2-standard-development/2 (accessed on 6 October 2026).
37. Jasiński, R.; Michalak, D.; Ludwiczak, A.; Ziółkowski, A.; Wysibirski, R. Hydrogen in Transport: A Comprehensive Review of Technologies, Infrastructure and Future Prospects. *Energies* **2026**, *19*, 2089. [CrossRef]
38. European Union. *Directive (EU) 2016/798 of the European Parliament and of the Council of 11 May 2016 on Railway Safety*; European Union: Brussels, Belgium, 2016.
39. Hydrogen in Rail Transport Faces a Major Safety Test. Available online: https://www.railway.supply/hydrogen-in-rail-transport-faces-a-major-safety-test/ (accessed on 15 October 2026).
40. Wang, J.; Gao, Y.; Sun, S.; Shi, L. Safety Technologies and Challenges of Hydrogen-Powered Rail Transport. In *Proceedings of the 10th Hydrogen Technology Convention, Volume 1. WHTC 2023*; Sun, H., Pei, W., Dong, Y., Yu, H., You, S., Eds.; Springer Proceedings in Physics; Springer: Singapore, 2024; Volume 393. [CrossRef] [PubMed]
41. Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the Deployment of Alternative Fuels Infrastructure, and Repealing Directive 2014/94/EU. Available online: https://eur-lex.europa.eu/legalcontent/EN/TXT/PDF/?uri=CELEX:02023R1804-20260108 (accessed on 7 October 2026).
42. Directive (EU) 2016/797 of the European Parliament and of the Council of 11 May 2016 on the Interoperability of the Rail System Within the European Union. Available online: https://eurlex.europa.eu/legalcontent/EN/TXT/PDF/?uri=CELEX:02016L0797-20260802 (accessed on 7 October 2026).
43. International Union of Railways. UIC Hydrogen Risks-Guidelines for the safe introduction of hydrogen technologies in railways. In *Annex II Standards & Codes of Practices*; International Union of Railways: Paris, France, 2025.
44. European Union. *COMMISSION DECISION 2009/460/EC of 5 June 2009 on the Adoption of a Common Safety Method for Assessment of Achievement of Safety Targets, as Referred to in Article 6 of Directive 2004/49/EC of the European Parliament and of the Council*; European Union: Brussels, Belgium, 2009.
45. *EN 45545 (Series)*; Railway Applications. Fire Protection on Railway Vehicles. European Committee for Standardization: Brussels, Belgium, 2024.
46. Jeon, B.-I.; Kim, S.; Yoon, Y.S.; Jung, S. Quantitative Risk Assessment of Hydrogen Refueling Station in Cheonan City of South Korea. *Energies* **2023**, *16*, 7138. [CrossRef]
47. Riccardi, L.; Compare, M.; Mascherona, R.; Zio, E. Structural Causal Modeling and STPA for the Risk Analysis of a Rail System Powered by H2 Fuel. *Reliab. Eng. Syst. Saf.* **2025**, *256*, 110758. [CrossRef]
48. *UN ECE R134*; Addendum 133–Regulation No. 134 Revision 1 Uniform Provisions Concerning the Approval of Motor Vehicles and Their Components with Regard to the Safety-Related Performance of Hydrogen Fuelled Vehicles (HFCV). Available online: https://unece.org/sites/default/files/2025-03/R134r1e.pdf (accessed on 9 October 2026).
49. *ISO 19881:2025*; Gaseous Hydrogen—Land Vehicle Fuel Containers. ISO: Geneva, Switzerland, 2025. Available online: https://www.iso.org/standard/19881 (accessed on 17 October 2026).

50. *ISO 19880-1:2020*; Gaseous Hydrogen—Fuelling Stations Part 1: General Requirements. ISO: Geneva, Switzerland, 2020. Available online: https://www.iso.org/standard/71940.html (accessed on 9 October 2026).
51. Qu, J.; Zhou, T.; Wang, C.; Luo, Z.; Li, R.; Zhao, H.; Li, H.; Wang, L.; Deng, J. Research on the explosion characteristics of petrol vapour-hydrogen mixture under multi-factor coupling. *Fuel* **2027**, *428*, 140327. [CrossRef]

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