

STANDARDS RESEARCH

Advancing the Use of Hydrogen and Electrification in the Rail Industry

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Executive Summary

The compounding effects of climate change and the resulting global push to reduce greenhouse gas emissions have spurred a need to advance zero-emission (ZE) propulsion technologies across all transportation modes. Both the Canadian and American federal emission reduction targets and long-term strategies to decarbonize the transportation sector identify ZE propulsion in the rail sector as part of their action plans.

The advancement, widespread adoption, and safe and reliable use of ZE rail propulsion technologies depends on the development of codes and standards specific to these technologies operating in a rail environment. This report provides an overview of the current landscape of codes and standards relevant to two prominent ZE propulsion technologies: hydrogen fuel cells and batteries.

As an initial step, gaps in the current codes and standards landscape were identified through a review of the existing codes and standards applicable to ZE technologies and interviews with industry experts. Based on an analysis of the existing landscape and expert input from a variety of industry sources, gaps were prioritized according to their importance and urgency with respect to ZE rail technology advancement, and a roadmap for developing applicable codes and standards was created.

The topics rated as most important for standardization development included component and subsystem design, crashworthiness, hydrogen refuelling, and battery charging. The development of codes and standards related to these key topics will be crucial in supporting safe and dependable use of these propulsion technologies.



"In 2021 Canada's rail sector emitted 7.8 megatonnes (Mt) of carbon dioxide equivalent (CO_2e) GHGs, 98% of which came from freight operations. Canadian rail transportation was also responsible for over 79,000 tonnes of nitrogen oxides (NO_x), accounting for 6% of Canada's total NO_x emissions that year"

1 Introduction

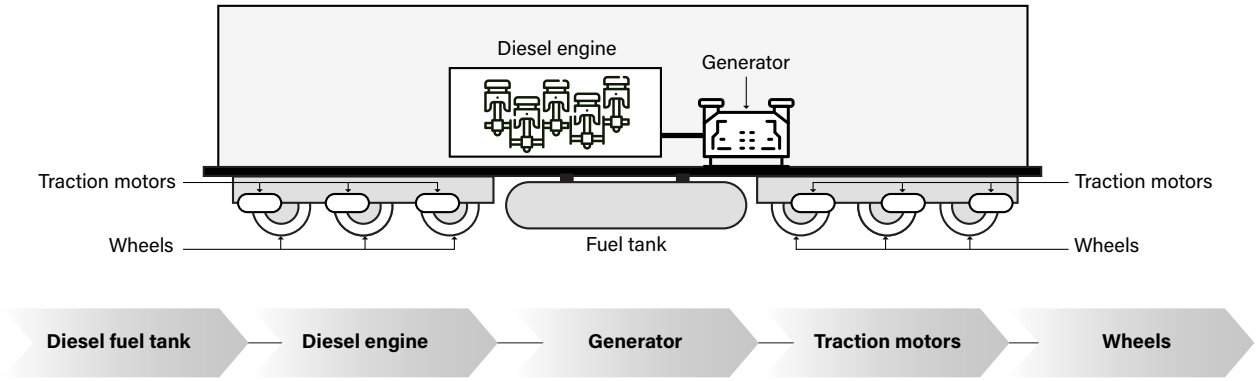
Globally, the impacts of climate change are becoming increasingly apparent, resulting in an urgent need to reduce greenhouse gas (GHG) emissions across all sectors. In 2021, Canada's rail sector emitted 7.8 megatonnes (Mt) of carbon dioxide equivalent (CO_{2e}) GHGs, 98% of which came from freight operations [1]. Canadian rail transportation was also responsible for over 79,000 tonnes of nitrogen oxides (NO_x), accounting for 6% of Canada's total NO_x emissions that year [3]. In 2020, the United States rail sector emitted 34.2 Mt of CO_{2e} [2]. As required under Canada's Locomotive Emissions Regulations, locomotive emissions of criteria air contaminants (CACs) are frequently tested and reported. To assist in monitoring emissions, Transport Canada (TC) has adopted the US Environmental Protection Agency (EPA) locomotive emission Tier classifications defined in Title 40 Part 1033 of the US Code of Federal Regulations (CFR) that specify maximum emission levels of criteria pollutants that locomotives can produce based on the year of engine manufacture or rebuild. As of 2020, approximately 8.4% of Canada's locomotive fleet was classified as Tier 4—the cleanest (i.e., least polluting) diesel locomotive classification—and 0.3% were non-diesel powered [4]. The remaining 91.3% of operating locomotives do not meet the current cleanest emissions standards (i.e., they pollute more).

Fossil fuel-based propulsion systems convert the chemical energy in the fuel into mechanical energy through combustion using an engine. By attaching a generator to the engine, the mechanical energy is then converted to electrical energy (either direct current (DC) or alternating current (AC)) that powers electric traction motors. This is why diesel-powered locomotives are referred to as diesel-electric locomotives. A diagram showing a generalized diesel-electric locomotive with a simplified block diagram of its powertrain is included as Figure 1. Since exhaust emissions from the diesel engine are the main source of rail sector emissions, newer technologies capable of providing electricity to traction motors without creating emissions are being explored.

The Government of Canada's 2030 Emissions Reduction Plan strives to reduce Canada's emissions by 40% below 2005 levels by 2030 and reach net-zero by 2050 [5]. To achieve these goals, the Canadian government created a sector-specific roadmap that includes the development of a rail decarbonization action plan aligned with the 2050 net-zero goal that "could include efforts to advance zero-emission locomotives and locomotive electrification [5]."

In its long-term climate strategy, the United States has committed to reducing its net GHG emissions by 50-52% below 2005 levels by 2030, and set a goal to reach net-zero by 2050 at the latest [6]. The US strategy identified electrifying segments of the existing rail network and prioritizing other energy carriers, including hydrogen, as elements of its decarbonization strategy, noting that "measures like high-speed rail and transit-oriented development not only reduce emissions but also create more connected, accessible, and healthier communities [6]."

Figure 1: Diesel-electric locomotive with simplified powertrain



Canada's rail industry is primed to continue its explorations and global leadership in developing zero-emission (ZE) rail propulsion. The Hydrogen Strategy for Canada states that, as a novel technology, "there are some gaps in existing codes & standards that need to be addressed to enable adoption" of hydrogen [7]. Therefore, there is an opportunity to support the Canadian, US, and global rail sectors in transitioning to ZE propulsion by developing codes and standards for the design, testing, and implementation of these technologies in a rail context.

The US Federal Railroad Administration (FRA) and TC hold federal responsibility for ensuring the safe functioning of railroads. To uphold this responsibility, the Canadian regulatory regime requires compliance with industry-accepted standards, among other regulatory tools. Traditionally, these regulations have not pinpointed a specific energy source, although they often implicitly assume the use of diesel fuel due to its widespread use. The regulations lay out test methods and performance criteria for equipment used on federally regulated tracks.

The FRA is in the process of preparing for the possible use of ZE technology (e.g., hydrogen, battery) in US railroads. In 2013, the FRA sent a letter to the industry about alternative fuels, providing a list of necessary evaluations [8]. Originally, this list focused on natural gas, but it has since been updated to include hydrogen. Currently, when plans for introducing new equipment or technology are presented, the FRA provides oversight on specific test scenarios and on the use of new technologies on federally regulated rail lines. For example, the FRA may witness certain testing and review test results before permitting new technologies to be used in public spaces.

To add to the discussion of the adoption of these new technologies in a rail context, research was focused on literature and existing documentation relating to battery and hydrogen-fuelled technologies for rail vehicles and the equipment required to energize the vehicle (e.g., refuelling or charging infrastructure). Codes and standards pertaining to production or generation facilities or other wayside infrastructure, and established propulsion technologies such as overhead catenary systems and third-rail systems, were beyond the scope of this research.

The objective of this report is to support the rail industry's participation in implementing and advancing clean propulsion technologies. This report will provide an industry-backed roadmap detailing prioritized, actionable recommendations for the codes and standards topics most critical to the North American rail industry's implementation of emission reduction technologies.

2 Methodology

The research informing this project was conducted through two concurrent activity streams: development of a database of applicable codes and standards, and consultation with interested parties from the rail and ZE technology sectors. The streams were completed in parallel. Ongoing results from each guided and influenced the other throughout the project, and the results from both streams were combined.

The database of applicable codes and standards was developed by compiling an initial dataset of code and standard titles (with scopes where available) from multiple Standards Development Organizations (SDOs) and a review of published literature, including relevant research reports. A subset of this dataset was manually reviewed. Subject matter experts manually classified the codes and standards in this subset as applicable or not applicable to ZE rail propulsion. A natural language processor (NLP) was trained on this manually categorized subset (the training dataset). The trained NLP was then used to review the entire dataset and identify additional codes and standards applicable to ZE rail propulsion that were not included in the training dataset. The applicable codes and standards from the training dataset and those identified by the NLP formed the database that was then manually reviewed and categorized based on the topics covered by each document.

Interested parties from the rail and ZE technology sectors were interviewed to collect information and opinions regarding codes and standards applicable to ZE rail propulsion (see Appendix A). The interested parties were asked to identify gaps in the codes and standards coverage based on their experience, as well as topics that could benefit from standardization (regardless of their perception of a gap). In addition to the interviews with interested parties, surveys were conducted wherein respondents were asked to identify and prioritize gaps in codes and standards pertaining to hydrogen and battery electrified rail applications. Applicable standards identified through interviews and surveys were also added to the database.

The applicable codes and standards from the database were sorted by topic and area of applicability, and are listed in Appendix B. The sorted database was used to check whether the gaps identified by interested parties were covered by existing codes and standards, and to assist in identifying additional gaps.

The gaps identified and confirmed by the database were then assessed for their impact on the advancement of ZE technologies in the rail industry and prioritized into a roadmap based on internal experience and external inputs via the interview, survey results, and a workshop with interested parties. The resulting roadmap identifies a prioritized list of topics for standards development in support of clean technology advancement in the rail sector.

3 Technology Background

3.1 Zero-Emission Motive Power for Rail

In the context of vehicle propulsion, ZE technology refers to equipment capable of powering vehicle propulsion without producing harmful point-of-use (or tailpipe) emissions. The scope of this definition is limited to the vehicle itself and does not account for emissions created upstream in the energy production process (e.g., emissions resulting from the production of the electricity or hydrogen used to power the vehicle).

To provide traction motors with electricity without producing point-of-use emissions, one or more of the following systems is used:

- energy storage on board the vehicle (e.g., batteries);
- electricity production on board the vehicle (e.g., using hydrogen fuel cells); and
- continuous transmission of electricity from wayside infrastructure to the vehicle (e.g., using an overhead catenary system).

The described systems, shown in Figures 2-4, replace the diesel engine and fuel tank in traditional diesel-electric locomotives shown in Figure 1. Note that in addition to ZE technology, there are low-emission technologies that include some of the technologies already discussed, such as diesel-electric battery hybrids. Since the diesel propulsion system is already well-established and the battery portion of those systems is equivalent to the hybridized version of a fuel cell-cell-battery hybrid, the hybridization of low-emission technologies, specifically the batteries, is covered in Section 3.1.1 of this report.

Figure 2: Hydrogen fuel cell battery hybrid locomotive with simplified powertrain

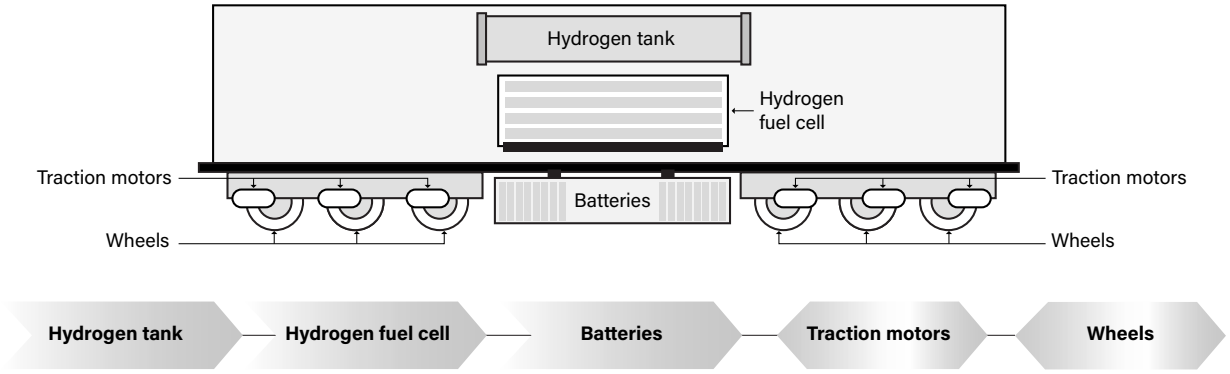


Figure 3: Hydrogen combustion engine battery hybrid locomotive with simplified powertrain

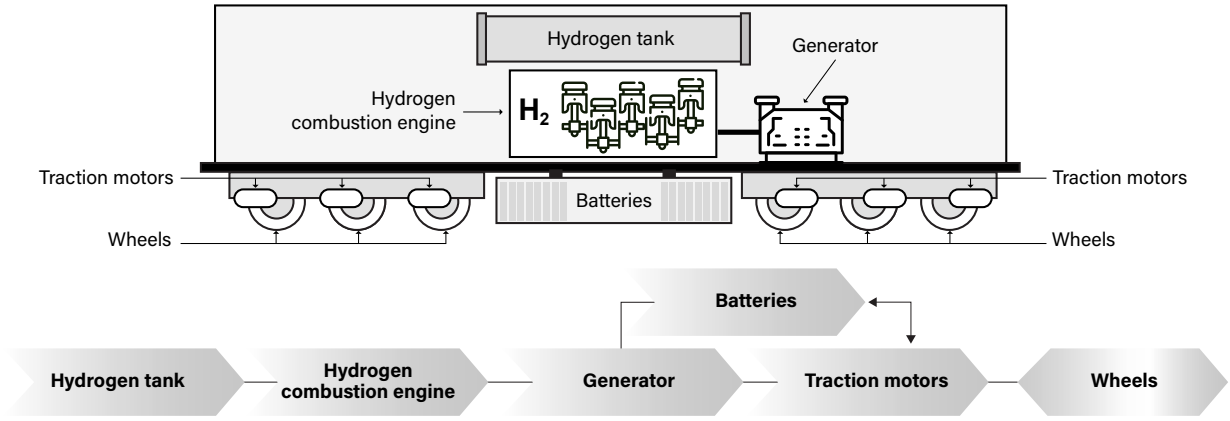
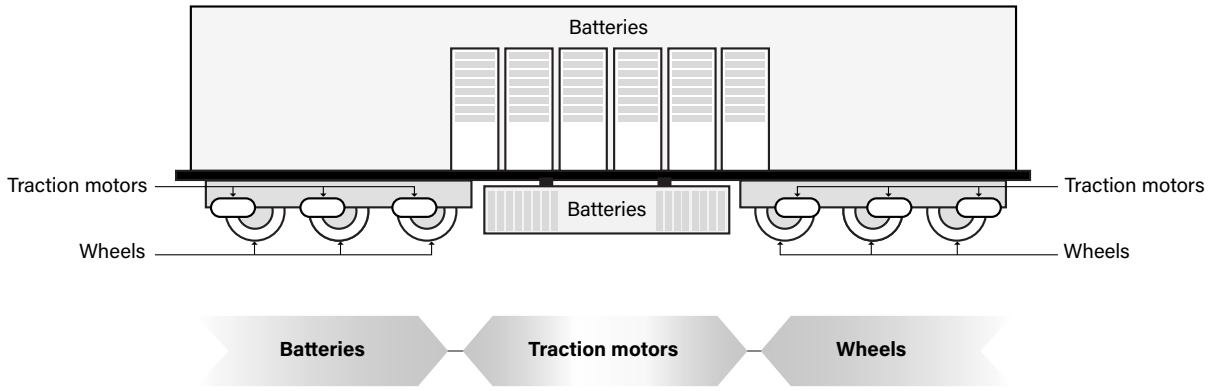


Figure 4: Battery-electric locomotive with simplified powertrain



Since battery and hydrogen technologies are in the early stages of widespread deployment in the rail sector, they are the focus of this report.

The introduction of battery and hydrogen technologies in a rail context leads to the need for a variety of new codes and standards to address topics critical to their widespread adoption and implementation and to help enable safe and efficient operations. For example, although batteries and hydrogen-fuelled technologies have been used in other contexts (e.g., stationary power supply, automotive), implementation in a rail setting presents new operating environments and the potential need for larger and more powerful systems. These new use cases introduce a need for codes and standards that address rail-specific considerations, such as component and system design and testing requirements that account for the rail operating environment. In general, the rail operating environment includes, but is not limited to:

- fluctuating temperatures;
- variations in altitude;
- mechanical shocks and vibrations
- indoor, outdoor, elevated, and underground operating settings;
- exposure to public spaces, roadways, and other vehicles;
- proximity to heavy-duty equipment, hazardous and volatile substances, and high-voltage systems;
- potential exposure to electrical shocks, vandalism, floods, fires, explosions, and lightning strikes;
- potential for involvement in collisions and derailments; and
- potential targeting for criminal activity (including cyber-attacks).

The potential hazards associated with rail, including the transportation of dangerous goods and the large quantity of mass and energy moving with trains, are exacerbated by the challenging operating environmental factors listed above.

3.1.1 Battery Propulsion

The use of rechargeable batteries as energy storage systems (ESSs) in traction applications has seen increasing levels of adoption in the automotive sector in the form of hybrid electric vehicles (HEVs) or battery-only electric vehicles (BEVs). Locomotive manufacturers such as Wabtec [11] and Progress Rail [12] have announced plans to produce battery-electric locomotives (BELs) for the freight sector and have already implemented pilot prototypes, indicating the viability and general market interest in BELs. Other manufacturers, including Stadler, Siemens, Alstom, Tig-M, and Brookville, have already begun producing battery-powered passenger transit vehicles [13, 14, 15, 16, 17], some of which are already in operation in North America. For example, Detroit's QLine streetcar service operates on a combination of overhead electrification, opportunity charging, and plug-in charging [18].

Batteries have been adopted in some light-rail passenger applications [16, 17], but there have been few implementations in the heavy-haul sector due to the significantly higher energy requirements. Furthermore, railway vehicles often experience higher levels of utilization than passenger road vehicles and therefore may have more restrictions around long recharging times as it could impact revenue. However, breakthroughs in lithium-ion (Li-ion) battery technology have increased energy and power density, and have reduced charging time, indicating that battery technologies are becoming more applicable to heavy industry use cases.

As interest in battery technologies increases, so too does investigations into improvements in Li-ion chemistries, which currently dominate traction applications [19] (e.g., lithium-nickel-manganese-cobalt-oxide (NMC) chemistries), and alternative chemistries, which are less dependent on expensive materials such as lithium, nickel, and cobalt (e.g., sodium-ion (Na-ion) chemistries) [20]. Currently, Li-ion alternatives like Na-ion have yet to achieve equivalent energy densities to Li-ion chemistries and are not yet in commercial operation in a vehicle environment [20], making them less likely to be applicable to a rail

use case in the near future. Therefore, this report will focus on the potential for Li-ion battery chemistries for traction applications.

Due to factors inherent to battery chemistry, the voltages of the individual battery cells are often too low to be useful for traction applications [21]. To overcome this limitation, battery cells are often packaged into modules, strings, and packs. Although no standardized definition exists, a battery module is often made up of cells connected in series or parallel circuits, or a combination, with welded connections that are packed together into a container. Battery modules connected in series form a string. Typically, a string will contain enough modules to meet the voltage requirement of the specific powertrain architecture. Multiple strings connected in parallel form a battery pack.

Battery packs for propulsion applications often have high voltages (e.g., 400 to 800 V [22, 23, 24]) and must therefore be treated as a potential electrical shock hazard that could cause injury or death [25]. Due to the high voltages of these systems, special attention must be paid to the electrical design of battery packs to ensure electrical hazards, such as short circuit conditions, do not occur. This is especially important in the case of railway vehicles, particularly older freight locomotives, as they commonly have electrically conductive outer structures that may further increase the risk of electrical shock. To mitigate the electrical hazards associated with charged battery packs, grounding and bonding is employed to ensure accidental contact with the system does not introduce a new pathway of least resistance.

Individual cells of the same chemistry and format may have minute variations between them stemming from manufacturing tolerances in the production process. Although these variations are typically minor, they can result in an unbalanced charge-discharge behaviour between cells, where some cells in a battery pack may experience overcharging while others experience undercharging, which can cause those cells to degrade faster than the rest of the bank. In certain situations, overcharging a battery cell could result in a battery fire that could spread to other cells in the bank resulting in a cascade of battery combustion [26]. A battery management system (BMS) is often employed to balance the charge between the cells and to electrically disconnect and isolate any part of the battery bank before unsafe conditions are reached.

The chemical reactions inside battery cells are typically sensitive to ambient temperatures [27]. Depending on the chemistry, cold weather conditions typically reduce the power output and often restrict or even completely prohibit charging. Higher temperatures often reduce battery cycle life and increase the risk of battery fires. Therefore, batteries for traction applications often require thermal management systems. A battery thermal management system (BTMS) regulates the temperature of the battery bank and ensures its safe operation. BELs present a rather unique challenge from a thermal management point of view as locomotives could potentially contain upwards of two megawatt-hours (MWhs) of stored energy, enough to power an average Canadian household for approximately one month. The sheer size of the battery bank may further highlights the importance of thermally regulating the batteries to ensure safe operations. Additionally, if such locomotives are to be used in cold climates such as Canada's, the BTMS must continually ensure that the battery cells do not experience extreme cold conditions.

Li-ion batteries present additional challenges from a fire safety point of view due to their susceptibility to thermal runaway, fast burning, and ability to re-ignite [28, 19]. Thermal runaway can occur when the temperature of a cell within the battery rises beyond a certain level. As the temperature of the cell increases, it reaches a failure point and begins to release hot gases and other harmful chemicals that can set off a chain reaction resulting in temperature increase amongst neighbouring cells, cell failure, and fire throughout the battery pack. As hot gases are released from individual cells, the internal pressure within the battery can increase and create an explosion risk [19]. Thermal runaway can result from mechanical abuse (puncture or penetration of the cell), electrical abuse (short circuit conditions), or thermal abuse (ambient conditions are too hot). Fire early-warning systems and effective fire-extinguishing agents for Li-ion battery fires are not yet completely developed or understood and are active areas of research [29, 19]. Often the released gases are toxic and appropriate hazard mitigation must be employed (e.g., enclosed spaces may have to be temperature controlled, have a ventilation system, and possibly have firewalls).



"The energy content in one kilogram of hydrogen is nearly three times greater than that of diesel."

3.1.2 Hydrogen Propulsion

This section provides an introductory overview of the components that make up a hydrogen fuel cell powertrain.

3.1.2.1 Hydrogen

Hydrogen is the lightest and most common element in the universe, forming a colourless, odourless, low-density gas at atmospheric temperatures and pressures [30]. It shows promising potential as a transportation fuel due to its high specific energy (i.e., energy per unit of mass). The energy content in one kilogram of hydrogen is nearly three times greater than that of diesel [31].

However, there are limitations to the use of hydrogen as a fuel due, in part, to its low energy density (i.e., energy per unit of volume). One kilogram of hydrogen at atmospheric temperature and pressure (ATP) takes up approximately 10,000 times more volume than one kilogram of diesel [32, 33]. Combined, this means hydrogen has an energy density approximately 3,600 times lower than diesel.

To be practical as a fuel given these physical properties, hydrogen is either compressed to form a pressurized gas, cooled to its liquid state, or combined with other molecules for storage in other chemical compositions.

3.1.2.2 Hydrogen Storage

Hydrogen is typically stored on board vehicles as a compressed gas in tanks at a pressure of either 35 MPa or 70 MPa [34]. For stationary applications in large quantities, hydrogen is typically stored in liquid form at atmospheric pressure. As a liquid, hydrogen must be kept at or below its boiling temperature of -252.85°C (-423°F) to keep it from converting to its gaseous state. Because of the high energy density in this state, hydrogen is commonly transported as a liquid, especially when large quantities need to be transported [35]. The aerospace, heavy industry, and automotive sectors have previously tested use of liquid hydrogen as a fuel and incorporated on-board storage [36, 37]. However, the low temperature makes liquid hydrogen a much more complex and hazardous fuel option [38]. Certain hydrogen-rich compounds, such as ammonia or metal hydrides, can be used as a chemical storage method. These technologies are primarily in the research and development stage and are the focus of numerous government-funded development and advancement initiatives [39].

The materials selected for storing hydrogen must be carefully researched and selected. The small size of the hydrogen atom allows it to permeate and dissolve into most metallic and alloy materials, changing the properties of the materials and ultimately reducing their ductility and load-bearing capacity—a phenomenon referred to as hydrogen embrittlement [40], which is especially important during times of long exposure to hydrogen such as in tanks.

Due to the difference in hydrogen's physical properties from diesel, hydrogen rail vehicle fuel tanks will require significantly different designs, testing, and locations within the vehicles, all of which require codes and standards.

3.1.2.3 Hydrogen Fuel Cells

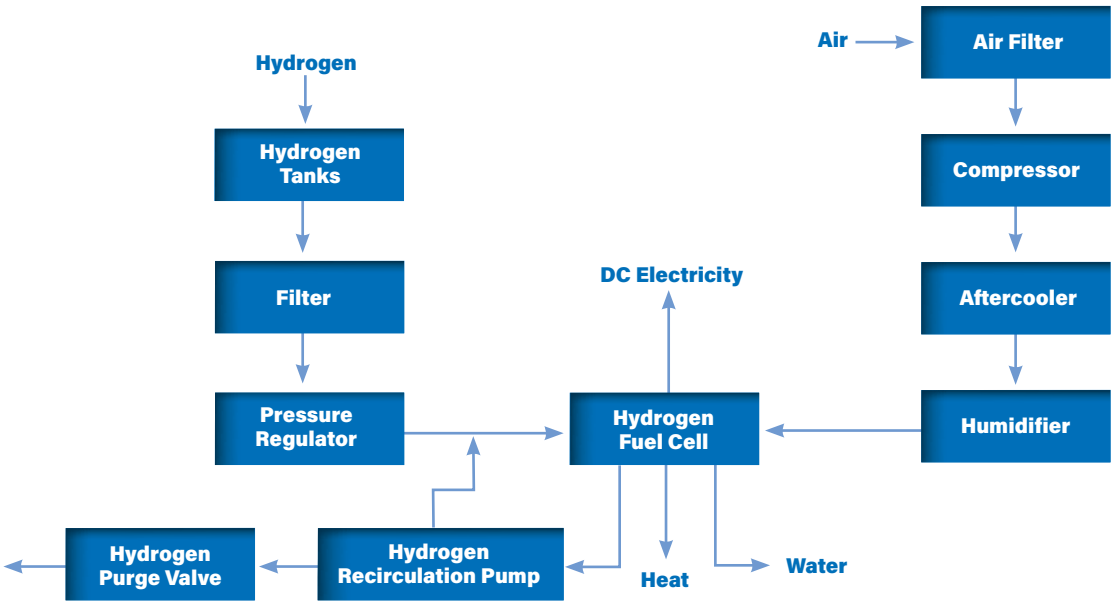
Hydrogen fuel cells (HFCs) combine hydrogen and an oxygen source (typically from ambient air) in the presence of catalysts to create an exothermic reaction, meaning energy is released in the process [41]. Some of this energy is released as heat, and some takes the form of electricity that can be used to charge a battery or power an electric motor (see Figure 5). Overall, the inputs to the HFC are hydrogen and oxygen, and the primary output is electrical energy. The chemical process also results in the formation of water (typically in the form of vapour) and heat, which are considered byproducts of the energy production process. No GHGs or other air pollutants are emitted by HFCs.

There are a variety of HFC types, with the primary difference being the materials (e.g., catalysts, electrolytes) used in the HFC. Different combinations of materials yield different operating characteristics (e.g., operating temperature, efficiency, start-up time, sensitivity to fuel impurities) and ideal use cases. The US Department of Energy produced a fact sheet detailing and comparing common fuel cell type [42]. To date, the most common HFC type used in transportation applications is the proton exchange membrane fuel cell (PEMFC), also called a polymer electrolyte membrane fuel cell [43], mainly due to its relatively low operating temperatures (-40°C to 120°C) and high efficiencies (up to ~65%, to date), high power density, and scalability [44]. PEMFCs require ultra-pure hydrogen as a fuel [45], and thus hydrogen quality standards and quality test methods (i.e., SAE J2719, ISO 14687) have been developed to aid in the implementation of HFCs as a reliable power system.

PEMFCs are more easily scalable because they can be combined into stacks, allowing for the sharing of reactant inlets and series-connection of electrical outputs. To control the HFCs and monitor their operations, a balance of plant (BoP) system—auxiliary components that support HFC electricity generation—is paired with HFC stacks. The primary objectives of the BoP are to:

- ensure reactants are supplied to the HFCs at the optimal temperature, humidity, and pressure;
- cool the stacks;
- remove water as it forms in the HFCs; and
- control the HFCs [46].

Figure 5: Fuel Cell System and Associated Balance of Plant Components



These systems include gas circulation and control equipment, compressors, heat exchangers, humidifiers, power conditioning devices and electronic control equipment, among other devices, as described in standards like SAE J2616. Manufacturers commonly combine the HFC stacks and BoP into one module, which is categorized by net power level (e.g., in kW). The design and integration of modules into the vehicle is paramount to HFC operation and a key reason for standardization in a rail environment.

3.1.2.4 Hydrogen Combustion

Hydrogen can be used as a fuel in internal combustion engines (ICEs), either by itself in a hydrogen internal combustion engine (H-ICE) [47, 48] or as a blend in a diesel-hydrogen dual fuel internal combustion engine (DH-ICE) [49].

DH-ICEs can be created by converting existing diesel engines and adding on-board hydrogen storage tanks [49]. Since the existing locomotive and some of its components would be retained, this technology option could be a lower-emission way of keeping existing locomotives in service for their expected lifespan. Notably, hydrogen used for combustion does not need to be ultra-pure [49], as opposed to the ultra-pure hydrogen required for use in a fuel cell, as discussed previously. DH-ICEs have been shown to have up to 86% lower carbon dioxide (CO_2) emissions than the pre-existing, non-converted, diesel engines [49]. Their impact on other emissions, such as oxides of nitrogen (NO_x), is less clear, with published research indicating the technology may produce less or significantly more NO_x emissions than a comparable engine running on diesel fuel alone depending on factors such as the load on the engine [50]. Since DH-ICEs still burn diesel and create emissions, they are not considered a ZE technology.

The combustion of hydrogen in H-ICEs theoretically would not produce CO_2, carbon monoxide (CO), or particulate matter [47, 48], although small amounts of these emissions can be created by the combustion of the lubricants used in the engine. Mechanically, H-ICEs are similar to diesel ICEs [47], with changes made to account for the differences between hydrogen and diesel in fuel delivery, ignition, and combustion requirements. In rail applications, H-ICEs could replace the diesel engines, and hydrogen storage would then be required rather than diesel fuel tanks.

3.1.2.5 Hybridized Propulsion Systems

As with ICEs, the efficiency of HFCs varies with the load applied. Starting from a stop, accelerating while in motion, and gaining elevation all increase the load on the power supply. Specifically, dynamic loading negatively impacts the efficiency [51] and lifespan of HFCs, meaning they are not ideal sources of direct power for traction motors. For this reason, HFCs are commonly combined with ESSs, such as batteries, which are capable of handling dynamic loads and act as buffers for the HFC. This setup allows the HFC system to operate efficiently without limiting the power provided to the traction motors. The pairing of HFCs with batteries has been employed in passenger rail [52], freight rail [53], and heavy-duty road vehicle [54] applications. In this configuration, propulsion energy comes from hydrogen, which is fed to the HFC. The HFC creates electricity that is used to charge the batteries and propel the vehicle. The batteries, charged by the HFC, meet the dynamic power requirements to move the vehicle, including during acceleration and climbing grades when more power is needed.

As an additional benefit, the batteries allow for the capture and reuse of braking energy that would otherwise be dissipated and lost as heat. Using a process known as regenerative braking, the flow of electricity within the propulsion system can effectively be reversed. The kinetic energy of the vehicle is captured by the traction motors (the mechanical motion of the axle turns the traction motor, which acts as a generator) to produce electricity that is fed to the batteries. While traditional diesel-electric locomotives can use their traction motors for braking, there is nothing on board the vehicle to store the electricity, so it is directed to a resistor grid and dissipated as waste heat. With an ESS, energy captured from braking can be stored and reused, making the overall system more efficient. Hybrid powertrains can also be formed with diesel engines and batteries for similar reasons as with HFCs, to increase efficiency and to reduce emissions. An example of a combustion engine hybrid vehicle is the Toyota Prius, and some diesel hybrid vehicles have been deployed in the railway sector [55].

3.1.2.6 Hydrogen Refuelling

To use hydrogen as a fuel for rail vehicles, equipment for transferring hydrogen into and out of the vehicle is required. Hydrogen is typically stored in large quantities as a liquid or a gas, but may be stored on board vehicles in a different state from which it is kept in bulk storage. The design of the refuelling system will depend on both the type of bulk storage and on-board storage methods (e.g., gas at 35MPa or 70MPa or liquid). The objective of these systems is to transfer hydrogen from its bulk storage state to the state used on board the vehicle, accounting for changes in state, pressure, temperature, etc.

Beyond the selection and sizing of specific components, the installation and operating environment of dispensing systems is also a safety topic with developing standards. See sections 4.2.2.2 and 4.2.3.8 for more information.

4 Existing Codes and Standards Landscape

4.1 Previously Identified Gaps in Hydrogen and Battery Standardization

A review of recent literature regarding the codes and standards applicable to hydrogen and battery rail technology, and potential coverage gaps that have been stated to exist [7], was conducted. The literature review included standardization landscape reports published by the National Research Council of Canada (NRC) that focused on hydrogen use across applications [56] and hydrogen and battery rail-specific applications [57], as well as reports from the US and UK railroad safety institutions [58, 59]. The reports provided insight into relevant codes and standards published by SDOs across the world and identified standardization gaps for hydrogen and battery use in rail applications.

The need for harmonization of codes and standards across regions, hydrogen tank maintenance, refuelling nozzles, and breakaway devices were identified in the report focusing on the entire value chain of hydrogen from production to use, and rail was discussed both as a method of transporting bulk hydrogen and as a use case with hydrogen-fuelled rail vehicles [56].

The report stated that because rail-specific hydrogen standards are missing, overarching or general hydrogen standards are often referenced.

Gaps in overarching, vehicle-specific, infrastructure-specific, and other codes and standards were identified in a report on standards pertaining to hydrogen and battery-powered rail applications [57]. Hydrogen sensors, pressure relief devices, fire alarm systems, air compressors, and hydrogen compressors were identified as gap areas for overarching codes and standards. Hydrogen dispensers were identified as a gap area for infrastructure codes and standards. Hydrogen storage systems and the associated components, fuel cell power systems, ventilation systems, heat exchangers, and water treatment systems were identified as gap areas for vehicle codes and standards. Batteries and bulk transport were identified as other gap areas for codes and standards. This report was rail-specific, with a focus on Canadian and North American applications, and did call out the need to address risks that may be increased in Canada, including winter conditions.

Ventilation, hydrogen fuel tank location, vibration and shock testing, refuelling, including protection from unintentional movement and breakaway devices, material compatibility with hydrogen, and physical phenomena resulting from differences between hydrogen and diesel were reported as gap areas for codes and standards pertaining to HFC-powered rail vehicles in the US [58]. This report was rail-specific and focused on the standards published by the Association of American Railroads (AAR), while also referencing standards from the National Fire Protection Association (NFPA) among other standards applicable to the US.

Fuel cell placement, vehicle interface, passenger safety and evacuation, fire and explosion safety, grounding, hydrogen storage, leak detection, ventilation, refuelling and defuelling, system cyber-security, signage, and operating procedures were identified as gap areas for vehicle codes and standards pertaining primarily to HFC-powered rail vehicles in the UK [59]. Off-board hydrogen storage, incident management and emergency response, and infrastructure design were identified as gap areas for infrastructure codes and standards. This report was rail-specific, with a UK and European focus.

In addition to the discussed literature, previous work in the hydrogen [60] and battery [61] codes and standards fields has produced publicly available databases. At the time of writing, there were approximately 900 standard titles listed in these databases. Neither of these databases provided a gap analysis. However, it was noted that further development of codes and standards is required for safe hydrogen use [60]. A potential lack in the availability of battery material test standards or comparative tools was noted for batteries [61].

Although this report does not rely on the findings of previous efforts, the results were considered in conjunction with the findings of the research and analysis performed for this report, outlined in Section 4.2.

4.2 Review of Existing Codes and Standards Landscape

Codes and standards identified through this research are presented in the tables provided in Appendix B. The documents are grouped by publisher and are categorized into one of the following topics:

- overarching codes and standards;
- infrastructure-specific codes and standards; and
- vehicle-specific codes and standards.

There are areas where multiple standards apply and areas with few or no applicable codes and standards. This report assesses both scenarios since areas with multiple entries could mean an area is well covered but could also result in conflicting standards that would require harmonization and alignment in relation to rail applications. Areas covered by a few, or a single code or standard, are also assessed for their potential as being a gap in the existing codes and standards landscape.

4.2.1 Overarching Codes and Standards

Overarching codes and standards apply to both the vehicles and infrastructure within the railway network, or to processes used in developing the network (e.g., hazard and risk management processes). The landscape of overarching codes and standards is summarized according to the following topics:

- failure analysis methods;
- process safety management;
- functional safety;
- hydrogen fuel specification and quality;
- material compatibility; and
- emergency preparedness and response.

4.2.1.1 Failure Analysis Methods

Failure analysis is an exhaustive and systematic discipline aimed at identifying potential system failures, understanding their origins, determining the magnitude of a failure's impact, and outlining viable mitigation strategies. It forms an integral part of the engineering and technology development process, acting as a crucial first step whenever a new technology is introduced or when an existing system is extended with a novel application.

Given that hydrogen rail technology is in its infancy, a comprehensive and rigorous failure analysis can play a critical role in identifying and pre-empting potential issues, effectively mitigating risks and aiding in the seamless integration of the technology.

This precautionary process is pivotal in facilitating the successful deployment and overall effectiveness of hydrogen rail technology. The application of a robust failure analysis procedure can enhance the reliable, safe, and sustainable development of the new technology application.

Standard development organizations have developed comprehensive guidelines for various failure analysis methods, including hazard and operability studies (IEC 61882), failure mode and effects analysis (SAE J1739, IEC 60812), and fault tree analysis (IEC 61025). These guidelines provide the frameworks to help ensure consistent and rigorous failure analyses across facets of technology development and deployment. CSA Group has also adopted ISO guidelines (CSA ISO 31000), further illustrating the global acknowledgment of the importance of this process. Additionally, NFPA 551 provides a specific focus on fire risk assessments, adding another layer of verification to this complex process. These existing standards can be applied to railway applications.

4.2.1.2 Process Safety Management

Process Safety Management (PSM) is an integral component of industrial operations, emphasizing the protection of all personnel involved in a given process. It necessitates an in-depth examination of the process from a safety perspective, assessing every stage for potential hazards and implementing robust measures to mitigate those risks.

PSM involves categorizing the process and evaluating its potential impacts in a detailed and structured manner. This categorization often involves the identification of hazardous elements, equipment, substances, or actions within the process, and assessing their associated risks. The evaluation also takes into account how these aspects could potentially affect not only the immediate operators but also the wider environment and any surrounding communities.

The advent of hydrogen rail technology brings about an array of novel processes and potential challenges, necessitating careful assessment and management. One such process is refuelling with compressed hydrogen gas, which could lead to complications such as nozzle freezing as the gas pressurizes inside the onboard tank. Moreover, dealing with cryogenic hydrogen introduces a set of unique safety considerations, due to the extreme low temperatures involved in its storage and transportation.

These challenges have necessitated the creation of specialized standards to address the handling and use of hydrogen in these new contexts. One such standard is the Compressed Gas Association's CGA P-28, which provides guidance specifically tailored to the unique safety challenges presented by cryogenic hydrogen.

Furthermore, to manage the novel process of refuelling with hydrogen, specific protocols have been developed and encapsulated in standards such as the SAE J2601. This standard focuses on refuelling protocols, addressing potential issues and specifying methods to safely and effectively fuel vehicles with hydrogen.

In Canada, the installation process for hydrogen technologies is predominantly guided by the Canadian Hydrogen Installation Code (CAN/BNQ 1784-000). This code serves as a critical reference document, setting forth best practices and requirements for the installation of hydrogen infrastructure. Process safety management systems are guided by CSA Z767 that outlines requirements for facilities and worksites handling or storing hazardous materials with potential or kinetic energy risks.

4.2.1.3 Functional Safety

Hydrogen rail propulsion (hydrail) technology represents an engineering domain that encompasses numerous subsystems such as the hydrogen supply system, fuel cell system, energy storage system, and both high- and low-voltage electrical systems. Ensuring the effective and safe operation of these subsystems necessitates intricate control mechanisms that are designed to facilitate the optimal functioning of each component.

For example, the fuel cell system demands hydrogen gas at specific pressure, temperature, and humidity levels. It requires an efficient system to interpret power demand signals by the locomotive engineer, converting them into power split commands that manage the balance between the fuel cell and battery systems. This functionality often hinges on programmable electronic safety-related systems, such as those outlined in the UL 1998 standard. These systems are responsible for maintaining secure operational conditions, as specified by guidelines like the IEC 61508 series of standards (Parts 1-7).

Furthermore, these electronic systems often have a broader operational scope, controlling machinery in accordance with standards like IEC 62061. These standards cover management of the flow of fuel and, in more critical situations, operation of ventilation systems to evacuate hydrogen leaks, an operation facilitated by leak detectors as stipulated in the UL 2075 standard.

Additional safety measures encompass short circuit detectors, fire safety systems, and hydrogen dispensing systems, which adhere to guidelines such as UL 2249. These safety measures further contribute to creating a robust and secure operational environment for hydrogen railways.

Considering the vehicle as a whole, additional standards like ISO 23273-1 provide a comprehensive framework for the safety and operation of hydrogen-powered vehicles. These standards underscore the complexity of hydrail technology, reflecting the multi-faceted nature of its operational components and the need for robust control and safety measures.



"In the context of hydrogen fuel cell transportation, components in both the refuelling infrastructure and on board the vehicle are required to have hydrogen material compatibility demonstrated or documented, as addressed in ANSI/CSA CHMC 1."

4.2.1.4 Hydrogen Fuel Specification and Quality

As discussed in Section 3.1.2, hydrogen fuel quality is critical to the performance and lifespan of HFCs, particularly PEMFCs [45, 62]. Multiple standards specify the quality of hydrogen to be used as a fuel for HFCs in stationary and vehicular settings (e.g., ISO 14687, SAE J2719), as well as the methodology for sampling and screening hydrogen fuels (e.g., ASTM D 7606, SAE J3219) and for controlling fuel quality in a refuelling station setting (ISO 19880-8). While none of the standards are specific to railway vehicle applications, they remain applicable.

4.2.1.5 Material Compatibility

Hydrogen, being the smallest molecule, interacts uniquely with different materials. It often alters their mechanical properties, necessitating a careful examination and selection of materials that will be in frequent contact with hydrogen. The material used for components involved in the storage, transport, supply, and use of hydrogen fuel should be chosen with extreme caution, considering whether they can safely withstand the temperatures, pressures, and potential material degradation (such as embrittlement risks) associated with hydrogen.

In the context of hydrogen fuel cell transportation, components in both the refuelling infrastructure and on board the vehicle are required to have hydrogen material compatibility demonstrated or documented, as addressed in ANSI/CSA CHMC 1. These components predominantly fall under the fuel storage and supply subsystems, including, but not limited to, compressors and pumps, valves, fittings, hydrogen storage containers, pressure gauges, fuel lines, fuel cell systems, hydrogen internal combustion engine systems, piping systems, and vaporizers.

To help address material compatibility with compressed hydrogen gas, CSA Group has published relevant standards, such as ANSI/CSA CHMC 1 and CSA/ANSI CHMC 2. Other international standards organizations, including ISO, JIS, and ASTM, have also released guidelines addressing this critical area.

ISO standards, including ISO TR-15916, ISO 21010, ISO 11114-2, ISO 11114-1, ISO 11114-3, and ISO 11439, tackle this topic, focusing on standardizing test methods for the detection of embrittlement, documenting reaction rates, and evaluating the overall material compatibility.

Similarly, JIS standards like JSA JIS H 7201, JSA JIS H 7203, and JSA JIS H 7202 offer specific guidelines for the measurement of various properties of hydrogen-absorbing alloys, as do ASTM standards, which include ASTM F1459, ASTM F519, ASTM G142, ASTM F1624, ASTM E2652, and ASTM B577.

The comprehensive implementation of these standards helps to address the safety, efficacy, and longevity of hydrogen fuel cell transportation systems, providing a roadmap for selecting and testing materials that will interact with hydrogen in various contexts.

4.2.1.6 Emergency Preparedness and Response

First responder training for emergency preparedness and response is essential to the health and welfare of emergency response personnel and the communities in which incidents occur. In situations such as a derailment, untrained responders could inadvertently exacerbate the situation, leading to unintended hydrogen release or circumstances that might trigger a detonation. Therefore, it is important to prepare individuals for such situations.

A pertinent document is SAE J2990, which provides guidance and standardized procedures for first and second responders to incidents involving lithium-ion battery-powered electric vehicles. It also covers hazards stemming from secondary events such as external fires or floods. It suggests the implementation of industry design standards and tools where appropriate. Emergency response to incidents involving other battery chemistries and alternative propulsion systems, including hydrogen fuel cell vehicles, are addressed by SAE J2990/1. Beyond the aforementioned automotive standards, CSA Z246.2 addresses emergency preparedness and response in industrial settings involving petroleum and natural gas, and common signage for emergency response to transportation incidents involving hazardous goods and materials is described in the Emergency Response Guidebook (ERG) published by the US Department of Transportation [63].

4.2.2 Infrastructure-Specific Codes and Standards

4.2.2.1 Maintenance Facilities

Maintenance facilities are integral to the upkeep of railway vehicles and represent a less understood facet of ZE propulsion technology implementation. Existing facilities may not be equipped to handle the unique properties and potential risks associated with hydrogen or batteries, such as adequate ventilation systems, sparkless tooling, climate control systems, and other safety measures employed in environments where hydrogen gas could be released or where batteries are stored. The differences in technology-specific facility requirements underscores the need for robust safety measures and modified operational practices specific to each technology.

These facilities must be equipped to address any unintended hydrogen release and must consider the safety ratings of different maintenance equipment and tools. The nature of hydrail technology may require a reassessment of regular railway maintenance activities. For example, tasks that have the potential to generate an ignition source, such as sparks resulting from wheel reprofiling and traction motor rewinding, might need to be conducted in a separate facility from tasks involving the motive power equipment to mitigate the risk of hydrogen-related incidents.

Existing standards applicable to hydrail maintenance facilities are limited. The CSA B401.1 and CSA B401.2 standards, although primarily dealing with maintenance facilities for natural gas and propane vehicles respectively, may offer some insights, and are referenced in the Canadian Hydrogen Installation Code (CAN/BNQ 1784-000). Additionally, CSA C22.1 and NFPA 497 may be applicable to such facilities, particularly for hazardous location classification.

Moreover, NFPA 80A provides an overarching guideline that should be considered when situating a maintenance facility near potential sources of ignition. Chapter 18 of NFPA 2 specifically discusses maintenance facilities for hydrogen vehicles, although it is focused on an automotive scale, which carry an order of magnitude less hydrogen compared to railway systems. This standard offers preventative measures against fire hazards and should be incorporated into the safety protocols of hydrail maintenance facilities.

4.2.2.2 Refuelling Stations

The refuelling equipment is a vital part of the supporting infrastructure for ZE vehicles. The process of refuelling hydrogen diverges significantly from that of refuelling liquid fossil fuels, such as diesel, which is the standard practice in the railroad industry. Since hydrogen is typically refuelled as a compressed, and often chilled, gas, a secured and sealed connection and additional safety checks between the fuelling station and vehicle are required.

Given the gaseous nature and unique properties of hydrogen, precise guidelines exist for the refuelling connection from the station to the vehicle (e.g., SAE J2600), as well as for other parts of the station itself (e.g., SAE J2799, ISO 19880-3, and ISO 19880-5), and for

refuelling protocols (e.g., SAE J2601). Communication between the station and the vehicle is vital to detect potential leaks during refuelling and ensure a safe filling process, preventing an over-pressurization event.

It is important to note that while existing standards primarily target on-road vehicles, they have been successfully applied to switcher locomotives and regional rail vehicles. However, these fill rates are likely not fast enough for rail vehicles, which may require rates in the order of 15 to 20 kg/min for smaller tanks (e.g., in switchers or regional trains). Long-distance vehicles with larger fuel tanks will likely require even higher fill rates to achieve fuelling in a practical amount of time, on par with diesel filling rates. Achieving higher rates might necessitate modifying current refuelling standards or introducing new standards for equipment capable of achieving higher fuelling rates.

Moreover, certain components within the refuelling station must be certified for hydrogen operations. This includes compressors and pumps, fuel dispensing equipment such as refuelling connection devices (covered by SAE J2600, CSA/ANSI HGV 4.1, CSA/ANSI LNG 4.1, CSA/ANSI NGV 4.1, and ANSI/CAN/CSA/ISO 12617), hoses for dispensers (ISO 19880-5), and valves.

CSA Group has put significant effort into addressing codes and standards pertaining to hydrogen fuelling stations. This work is primarily encompassed in the more general CSA/ANSI HGV 4.9 standard and extends to addressing specific components within the fuelling station such as valves (CSA/ANSI HGV 4.4). For fuelling with liquid hydrogen, ISO 13984 provides the necessary guidelines.

4.2.2.3 Battery Charging

With BEVs becoming more widespread, a variety of standards have been published for EV charging systems (e.g., IEC 61851, UL 2734, IEC 61980 series) and for the numerous plug and receptacle shapes and types used in EV charging systems (e.g., SAE J1772, IEC 62196-1). Although these standards are designed for automotive EV systems, which typically would not be powerful enough for rail applications, SAE J3271 is in progress with a scope that addresses megawatt-level DC charging systems, which could be suitably powerful for rail applications.

4.2.2.4 Equipment Performance

Several standards place a primary focus on the expected performance of equipment to ensure its safe and reliable operation. These guidelines typically outline specific requirements that both manufacturers and installers of parts must adhere to. While these standards revolve around performance metrics, safety is also a paramount consideration. Moreover, they aim to standardize parts across the supply chain and help maintain consistency in performance and safety across diverse applications.

For example, the Canadian Hydrogen Installation Code references multiple performance-based standards such as CSA/ANSI HGV 4.3. This standard stipulates methods to validate the performance of hydrogen refuelling stations and their associated equipment.

The Compressed Gas Association's CGA H-5 standard outlines the required performance of bulk hydrogen supply systems, including associated components such as valves, compressors and pumps, hydrogen storage containers, and piping systems.

Additionally, the performance of compressors and pumps is further addressed in international standards, including ISO 24490, ISO 13631, ISO 10439 (all four parts), ISO 10440-1, ISO 10440-2, ISO 10442, and ISO 13707.

Performance requirements of hydrogen dispensing systems, specifically refuelling connection devices, are addressed through standards such as SAE J2600, CSA/ANSI HGV 4.1, CSA/ANSI LNG 4.1, and CSA/ANSI NGV 4.1. Nevertheless, advancements in hydrogen fuelling technology that allow for quicker filling rates might necessitate changes to current codes and standards.

Finally, the performance of hydrogen generation equipment, often deployed in hydrogen production facilities, is defined by CSA/ANSI B22734 and UL 2264 for electrolyzer systems, and by ISO 16110-1, ISO 16110-2, and CSA/ANSI FC 5 for reformer-based production.

In essence, these performance-validation standards serve to uphold the safety and reliability of hydrogen equipment across different parts of the hydrogen infrastructure: from production to end-use applications.

4.2.3 Vehicle-Specific Codes and Standards

4.2.3.1 Electrical Safety

Hydrogen-powered and battery railway vehicles fundamentally function as electric vehicles since power is transferred from the energy source to the wheels via electricity. The magnitude of this electrical power can range from several hundred kilowatts to multi-megawatt systems, depending on the size of the vehicle in question. This necessitates an evaluation of electrical safety, given that improper handling of electrical power can present risks of electric shocks, electrocutions, and potential fires due to short-circuit conditions. These risks can exist while the vehicle is in operation, when parked, and following collisions—a scenario that requires special attention due to the increased risk of unintentional electrical contact when equipment is damaged. Moreover, multiple sources of electrical power exist within the vehicle that must be addressed, including batteries, fuel cells, and the electric traction motors used in regenerative braking.

The principal documents governing electrical safety are the Canadian Electrical Code (CSA C22.1) and the National Electrical Code (NFPA 70). Specifically pertaining to electric vehicles, standards such as ISO 6469-3 and SAE J2344 provide guidance on the vehicle as a whole, with particular standards (UL 458) discussing power electronic conversion devices. For battery-specific safety, IEC 62660-3 and IEC 62485-3 cover the safe installation, usage, inspection, and maintenance of this equipment. Specifically for railway operations, IEC 63341-1 and IEC 63341-2 address electrical safety of hydrogen fuel cell power systems and fuel storage systems. IEC 62282-4-101 and IEC 62282-5-100 provide requirements for hydrogen fuel cell systems safety for industrial trucking and general mobile power use cases.

Indeed, both high-voltage and low-voltage systems in a ZE railway vehicle have their own safety implications and complexities, and both should be handled with care. High-voltage systems can present immediate risks to life due to the large amount of energy involved, while low-voltage systems, although they may seem less dangerous, are also crucial to the safe operation of the vehicle as they control essential components.

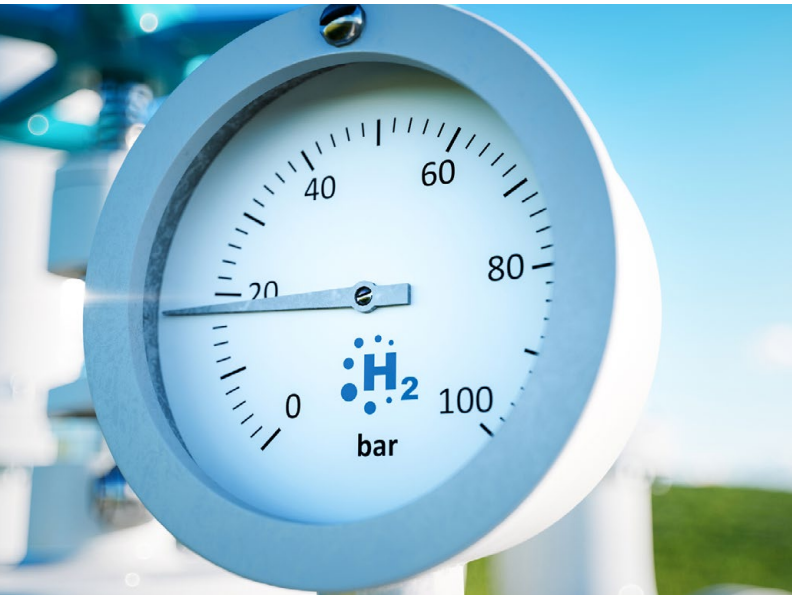
The high-voltage systems in ZE railway vehicles are responsible for the main drive and propulsion. These systems operate at voltages that can pose a direct electrocution hazard. Therefore, their safe operation, maintenance, and inspection are addressed in safety standards such as CSA C22.1, NFPA 70, ISO 6469-3, SAE J2344, and UL 458. Safety barriers, insulation, grounding, and safety interlocks are often used to minimize the risk of accidental contact with high-voltage parts.

On the other hand, low-voltage systems typically control auxiliary functions like lighting, horns, windshield wipers, hydrogen valve control, and battery management systems. Even though the voltages are lower, faults in these systems can still lead to fires, equipment damage, operational issues, and injuries to personnel. Therefore, safety in low-voltage systems is equally important. Standards like IEEE 16 address the safety requirements for low-voltage auxiliary circuits in railway applications.

In summary, when implementing and operating battery- or hydrogen-powered railway vehicles, it is essential to address the safety aspects of both high-voltage and low-voltage systems comprehensively and to adhere to the applicable requirements. The goal is to ensure that all electrical systems, regardless of their voltage level, are designed, installed, and maintained to provide safe and reliable service.

4.2.3.2 Pressurized Systems Safety

Pressurized systems are used in a variety of applications, ranging from industrial processes to transportation. At their most basic, these systems use pressure to perform specific functions, and the pressurized medium can be a gas, liquid, or even a slurry. In railway vehicles, pressurized systems are an integral part of vehicle operations. For example, the braking system on trains often uses pressurized air. Furthermore, existing hydrogen fuel cell railway vehicles use compressed hydrogen gas for fuel, which remains at pressures higher than atmospheric pressure until it reaches the fuel cell inlet.



"The safety implications of pressurized systems cannot be understated."

The safety implications of pressurized systems cannot be understated. Sudden depressurization caused by compromised structures, such as pipes or valves, can trigger a rapid release of energy, potentially causing parts to come flying apart and posing a risk to people and equipment [64].

The safety of pressurized systems is a topic of considerable importance, spanning design, construction, inspection, testing, maintenance, and operations. The ASME Boiler and Pressure Vessel Code (BPVC), referenced in CSA B51, outlines requirements for pressure vessel lifespans based on pressurization cycles and the testing performed for determining lifespan. Moreover, the CAN/BNQ 1784-000 covers various aspects related to hydrogen, including requirements for over-pressure protection of hydrogen installations.

Pressure relief devices (PRDs) are vital for safety, serving as a protection against over-pressurization. In compressed hydrogen vehicles, these can be thermally activated thermal pressure relief devices (TPRDs), and are typically located on top of the hydrogen tank. Standards from CSA, ISO, and CGA thoroughly cover these valves, which can be found, for example, on storage cylinders, tubes, and fuel lines. CSA/ANSI PRD 1 covers PRDs for NGV fuel containers, while CSA/ANSI HPRD 1 and ISO 19882 are specific to TPRDs for HGV fuel containers. Furthermore, ISO 4126-1 and ISO 4126-5 apply to valves with diameters of 4 mm or larger and pressures of 0.1 bar and above. CGA offers guidelines for PRD selection and sizing (CGA S-1.1), portable containers (CGA S-1.2), and stationary containers (CGA S-1.3). These should be taken into consideration alongside CGA PS-28, which provides a position statement on TPRDs that do not comply with section VIII of the ASME BPVC, and CGA PS-43, which provides guidance on the selection of PRDs specifically for tubes.

In the context of vehicle pressure regulators, pressure relief devices, sensors and gauges, CSA HPIT 1 offers guidelines for industrial trucks powered by compressed hydrogen. It outlines the minimum requirements for materials, design, manufacturing, and testing of components integral to a hydrogen storage and handling system, including various types of valves, fittings, storage containers, and fuel lines.

As noted, liquid hydrogen storage on railway vehicles can enhance the energy density of the fuel, thus enabling longer ranges. While there are not dedicated standards for pressure relief devices for portable liquid hydrogen tanks, the following standards for components of LNG road vehicle fuel systems may form a basis for standardization: CSA/ANSI LNG 3.3, CSA/ANSI LNG 3.4, CSA/ANSI LNG 3.7, CSA/ANSI LNG 3.8, CSA/ANSI LNG 3.13, and CSA/ANSI LNG 3.19.

4.2.3.3 Fire Safety

As previously noted, batteries, particularly those subject to electrical, mechanical, or thermal stress, represent a significant ignition and fire risk in electric vehicles.

The electrical system, encompassing elements such as cabling, converters, and energy storage systems, is another crucial area. UL 2734, for instance, provides guidelines for components like EV service plugs, connectors of an on-board EV charging system, and high-voltage components.

For a holistic understanding of electric vehicle safety, SAE J2344 provides recommendations for the design of vehicles under 10,000 lbs for use on public roads. However, for details specific to fuel cell vehicles, SAE J2578 recommended practice, ISO 23273-2, and UL 2267 standards offer technical guidelines regarding the safe integration of fuel cell systems and the management of hydrogen fuel storage and handling systems.

IEC 62660-3 and IEC 62485-3 offer safety requirements for batteries used in traction applications. They establish testing procedures for battery cells and packs intended for use in EV propulsion. IEC 62485-3 applies to battery-powered locomotives.

A wealth of standards exist that extensively cover the safety of lithium-ion battery-based energy storage systems, including but not limited to IEC 62660-3, IEC 62485-3, SAE J2380, SAE J2929, UL 583, SAE J2464, UL 62133-2, SAE J2344, UL 62133-1, UL 2271, AS 7486, UL 2580, UL 62133, and ISO 6469-1.

Another potential ignition source in a hydrogen fuel cell vehicle is the hydrogen fuel system. CSA/ANSI HGV 3.1 covers the safety aspects of fuel system components, such as valves, gas injectors, pressure gauges, fuel lines, and pressure relief devices. Even though it is not specific to hydrogen vehicles, CSA B109.1, which pertains to the vehicle installation code for CNG vehicles, may provide applicable concepts considering the compressed gas fuel's nature.

ISO 13985 specifically addresses the subject of liquid hydrogen in tanks on board land vehicles, potentially relevant to liquid hydrogen fuel tenders for railway propulsion. It delineates construction requirements and testing methods for such tanks. Additionally, CSA B109.2, which addresses vehicle installation for LNG vehicles, may offer applicable concepts for liquid hydrogen-powered vehicles. In terms of hydrogen fuel delivery in bulk, such as to a refuelling facility, CGA P-88 provides guidelines for both tube trailer and liquid deliveries.

SAE J2990 offers practices for first responders to EV fires, although it is crucial to note that codes and standards addressing EV fires are not overly abundant. SAE J2990 warrants further review for its applicability to railway vehicles, especially battery electric locomotives, which can contain multi-megawatt hours of stored energy.

Lastly, SAE J1766 offers a recommended practice for crash testing electric, fuel cell, and battery vehicles. This standard may be considered for its potential adaptation for railway applications.

4.2.3.4 Explosion Prevention and Control

Prevention and mitigation measures are required for both fire safety, which manages the risk of ignition, and explosion prevention and control, which addresses the separate threat of explosions.

Ignition is a chemical process that starts when a substance accumulates enough energy to trigger the reaction, emitting heat and light in the process. Conversely, an explosion is an abrupt and violent pressure change, commonly caused by the quick expansion of gases, often resulting in a shockwave [65].

Certain elements are necessary for an explosion to occur, including a fuel source like hydrogen or oxygen, and a source of ignition such as an electrical spark or fire. Explosion prevention involves regulating or removing one or more of these elements. A common mitigation strategy may be to ensure the fuel concentration in the air remains below its explosive limit. However, this can be difficult depending on the fuel's flammability range (e.g., hydrogen has an expansive flammability range of 4-75% concentration in air [32]).

Standards like NFPA 69, NFPA 55, NFPA 2, NFPA 52, and CAN/BNQ 1784-000 play a role in safe operation and explosion prevention. Fire safety is a primary focus because fires could potentially instigate explosions, especially if a hydrogen release coincides with or results from battery or electrical system fires.

The IEC 60079 series of Explosive Atmosphere Standards comprehensively cover the use of electrical systems in explosive atmospheres. Some parts have been adopted by CSA and UL with modifications (see Appendix B for the relevant amendments to the IEC 60079 series published as CSA C22.2 No. 60079 series of standards). These standards seek to help prevent electrical systems from creating unsafe conditions that cause explosions if located in an explosive atmosphere and can be considered in conjunction with NFPA 70. Furthermore, UL 913 discusses the concept of two-wire intrinsically safe ethernet, addressing potential ignitions in locations designated as hazardous. UL 1642, which covers primary and secondary battery cells, includes measures to mitigate fire or explosion risks.

The fuel source is another crucial component of the explosion equation. The likelihood of hydrogen leaks and consequent hydrogen gas entrapment within the vehicle could, under certain circumstances, lead to explosions. Therefore, the detection of flammable gases with gas detectors, as covered by CSA C22.2 NO. 60079-29-1, and CSA C22.2 NO. 60079-29-4, is another safety measure that aids in explosion prevention. In all situations, hydrogen needs to be vented in a safe manner, as covered by CGA G-5.5 and NFPA 91.

The threat of explosion isn't confined to the vehicle alone. Refuelling infrastructure, hydrogen-handling maintenance facilities, and the interface between the vehicle and the fuelling station also represent additional explosion risks. These could be due to trapped hydrogen leaks inside a maintenance shed or a faulty filling interface causing hydrogen leaks, which could potentially ignite. CGA PS-48 provides a recommendation on the setback distances for storage of bulk hydrogen fuel in response to unclear requirements in NFPA 55. CGA P-88 provides guidelines on the maintenance of bulk delivery equipment, including tube trailers used for delivery of compressed gas. CGA PS-69 provides separation distances for liquified hydrogen supply systems and may be reviewed in conjunction with CSA/ANSI LNG 3.5, CSA B51, NFPA 55, CSA/ANSI HGV 3.1, CSA B109.1, and CSA B109.2.

4.2.3.5 Structural Safety

Structural safety encompasses the robustness of a vehicle's chassis, body, and internal elements, as well as the possible hazards associated with their warping or impairment due to shocks and oscillations. There are three main types of loading that structural components may endure from shocks and vibrations:

- fatigue loading resulting from regular operations, such as the vibrations occurring when the vehicle traverses rail joints;
- expected shock loading occurring in typical operations, such as the loads caused by repeated acceleration and deceleration, especially within long trains subject to drawbar and buff forces, or from vehicle coupling and decoupling; and
- large impact forces resulting in deformations, typically caused by collisions or derailments.

ASME RT-1 and ASME RT-2 standards outline structural criteria for light and heavy rail transit vehicles, respectively. These are limited to vehicles designated for passenger transport and employ collision energy management schemes. While focusing on structural safety, they do not pertain to any specific type of propulsion. However, they may apply in protecting propulsion equipment within the vehicle (e.g., batteries installed in the car body where its structure provides protection for the batteries in case of impact).

On FRA-regulated tracks, minimum requirements for acceleration static load factors are described throughout 49 CFR Part 238 for passenger rail. These static load requirements apply to any components that are fixed to the car body, including powertrain components and subsystems such as batteries, HFCs, and fuel tanks, and their supporting systems. These requirements also align with Section 6.6.2 of AAR S-580, referenced in TC's Railway Locomotive Inspection and Safety Rules [66], which specify locomotive crashworthiness requirements for freight locomotives. In the context of passenger rail equipment, including locomotives, cab cars, multiple units, locomotive-hauled equipment, and non-passenger-carrying power cars, APTA PR-CS-S-034-99 specifies minimum acceleration static load factors for

on-board equipment and the car body structure in passenger-carrying equipment.

A primary focus of structural safety in conventional vehicles is the fuel tank due to the hazards resulting from the large amount of energy stored within it. Existing regulations relating to structural integrity and testing, such as 49 CFR Part 238, specifically refer to industry standards developed by SDOs such as APTA and AAR. Regarding the vehicle fuel reservoir, there are various standards and regulations, such as APTA PR-CS-S-007-98 and 49 CFR Part 229, that stipulate minimum structural fortitude, vehicle incorporation, and fabrication requirements. 49 CFR Part 238 also specifies requirements for fuel tanks. Notably, these standards are primarily tailored for tanks situated in the undercarriage as they refer to bottom and side loadings and consistently allude to the clearance between the tank and rails. Alternative propulsion system components, such as fuel cells, tanks, or batteries, may not be located in the undercarriage and could be mounted on the roof or in other areas of the vehicle body. Therefore, several of these protection standards may not be directly applicable, but could be considered for expansion on to include alternative propulsion systems. Furthermore, the load values in existing standards are tailored to steel, sometimes specifying characteristics such as the thickness and yield strength of material to be used. These requirements are not necessarily applicable to the materials used in batteries or compressed hydrogen storage tanks, the latter of which often consist of a non-metallic inner liner comprised of composite materials enclosed by an external carbon fibre wrapping [67].

SAE J1766 provides recommended practices for testing the crash integrity of vehicles with high-voltage systems, including electric, fuel cell, and hybrid electric vehicles. CSA/ANSI HGV 3.1 defines requirements for fuel system components in vehicles powered by compressed hydrogen gas.

Regarding fuel tenders, AAR M-1004 specifies minimum force loadings that the support structure for the inner tank of an LNG fuel tender must endure during impact without giving way. Since the LNG fuel tender would typically be coupled to a locomotive, the locomotive must also be capable of enduring similar loading as outlined in IEC 61373, which specifies shock and vibration testing requirements for rolling stock equipment, albeit with slight variations from the specifications listed in AAR M-1004. As of this writing, work is ongoing to expand this standard to include other propulsion technologies [68].

4.2.3.6 Labelling and Marking

Labelling and marking are critical practices for identifying and providing crucial information about products, components, or systems. In the context of EVs and fuel cell electric vehicles (FCEVs), labels attached to batteries and hydrogen storage tanks offer essential details about handling, installation, servicing, potential hazards, and disposal, and can provide vital information to emergency responders. The identifiers—usually in the form of symbols, words, or codes—communicate the nature of the contents, specific instructions for safe handling, and warnings about potential dangers. Thus, appropriate labelling and marking contribute significantly to risk mitigation and awareness of EVs and FCEVs.

Compliance with safety and performance standards is often signified through these labels (e.g., using markings, stamps, decals, or plates attached to the item), aiding in quality control, legal adherence, and maintenance protocols [69] . The addition of labels and placards may also result from the integration of a component into a subsystem or vehicle as a whole. Additionally, correct disposal procedures are communicated through these markings. Labels and markings can also provide vital information to emergency responders who rely on common hazard identification symbols and labels like those outlined in the Emergency Response Guidebook jointly developed by TC, the US Department of Transportation, and the Secretariat of Transport and Communications of Mexico, to quickly understand the risks and recommended response when dealing with hazardous materials [70].

Codes such as 49 CFR Part 172, which addresses hazardous materials communications and emergency response information, describes general labelling requirements, including label content and placement,

as well as requirements for specific items, such as lithium batteries and flammable gases. Canadian Transportation of Dangerous Goods Regulations and 49 CFR Part 173 describe packaging and marking requirements for batteries being transported [71]. Beyond the CFR, the *Bipartisan Infrastructure Law* requires the EPA to develop battery recycling and labelling guidelines by 2026 [72].

Marking and labelling requirements are also addressed as a part of standards such as SAE J1798, which provides recommendations for performance ratings of EV batteries, and CSA/ANSI HGV 2, which addresses the proper marking of compressed hydrogen storage tanks. Existing standards could be expanded to cover relatively common subsystem implementations, such as multiple battery cells, modules, strings, and thermal management into an energy storage system, or several hydrogen cylinders in bundles with appropriate safety devices.

4.2.3.7 Batteries and Energy Management

Standards that collectively address various safety, testing, and performance measures for both electric and fuel cell vehicles were identified. CSA SPE-343 outlines the requirements for energy management systems used in electric vehicles. The IEC 62660-1 and IEC 63341-2 provide the specifications for testing and performance of lithium-ion cells used in electric vehicles. IEC 62864-1 complements these by specifying procedures for mechanical shock and vibration testing of lithium-ion battery packs and modules. CSA recently published a technical specification for on-board lithium-ion traction batteries, CSA TS-602, as a deviation to IEC 62928 for North America. SAE J2464 provides recommended practices for rechargeable energy storage system abuse testing. Meanwhile, SAE J2929 defines safety standards for lithium-based battery propulsion systems, and ISO 12405-4 lays out test procedures for lithium-ion battery packs and systems for electrically propelled vehicles, contributing to their safety and longevity.

4.2.3.8 Hydrogen Storage

Specific to hydrogen powered vehicles, standards like ISO 16111 and CSA B51 set forth requirements for transportable gas storage devices for hydrogen. ISO 11439 complements this by detailing the design and construction requirements of composite gas cylinders for hydrogen storage. ISO 19882 covers TPRDs for pressurized hydrogen storage containers on vehicles as discussed in Section 4.2.3.2. Lastly, SAE J2579 defines requirements for hydrogen fuel systems, including the storage and handling systems.

5 Opportunities for Codes and Standards Development

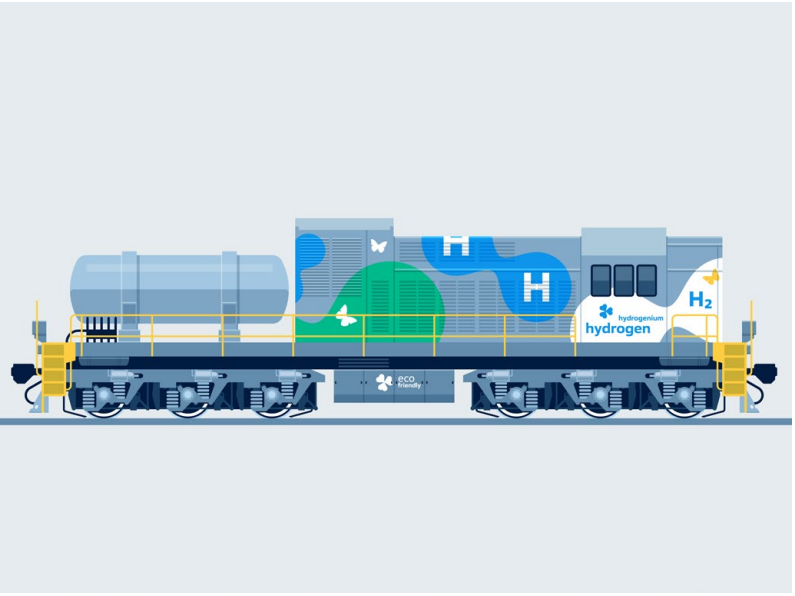
The following sections outline gaps identified in the existing literature landscape and provide a recommended roadmap to addressing those gaps and advancing the development and adoption of ZE propulsion technologies in the rail industry.

5.1 Gaps Identified in the Existing Landscape

The standards review and consultations with interested parties identified gaps in the existing codes and standards landscape applicable to hydrogen and battery technologies in a North American rail context. Although standards from other regions or industries may be relevant to a topic identified as a gap, deviations from the original standard may be required to ensure the standard is applicable to a North American railway application (e.g., a topic covered by European rail standards or North American automotive standards).

The gaps identified were categorized into the same categories as the existing codes and standards landscape groups:

- overarching codes and standards;
- infrastructure-specific codes and standards; and
- vehicle-specific codes and standards.



"To ensure widespread ZE technology adoption, standardization of the infrastructure, equipment, and processes supportive of rolling stock interchange will be required."

5.1.1 Overarching Codes and Standards

5.1.1.1 Interoperability and Operations:

Rolling stock assets in the railway industry, such as motive power vehicles and railcars, frequently interchange among different railroads, thereby creating a North American railway network that covers Canada, the US, and Mexico, and this interchange is facilitated by standards governed by the AAR. Railroads manage and move a significant amount of rolling stock on their network that does not belong to them (often belonging to other railroads, leasing companies, carpool operators, or customers), which necessitates standards to facilitate safe and efficient operation across the North American railway network and enable interchange of rolling stock between different companies or network owner. For example, standards help ensure that wheelsets have the correct width to operate on the track, individual rail cars can couple to each other, including brake connections, to form trains, and several locomotives in a consist or distributed throughout a train can be controlled from the leading motive power vehicle. To help ensure widespread ZE technology adoption, standardization of the infrastructure, equipment, and processes supportive of rolling stock interchange will be required. This will apply to, among others, the driver-vehicle interface, facility design and tooling, processes required for safe operation, refuelling and charging, maintenance, and repair. This challenge is more significant for freight railroads than passenger transit agencies due to the larger scale of rolling stock interchange. Sections 4.2.2.2 and 4.2.2.3 provide further detail on refuelling and charging infrastructure. Section 5.1.3.10 addresses the driver-vehicle interface.

Moreover, locomotives often operate in a consist where several locomotives are coupled together and in distributed power mode, where a trainset includes multiple locomotives that are distributed throughout the train (e.g., three locomotives in the front, one in the middle, and two at the end). In consist and distributed mode, signals from the leading locomotive control power demand signals for all other locomotives. To help ensure seamless operation within the same and mixed-technology groups, any new ZE railway vehicle should be compatible with this standardized communication interface, often referred to as multiple unit (MU) plugs when locomotives operate in a consist, and the appropriate radio control when operated as distributed power. Therefore, existing standards relating to communication interfaces must be compatible with ZE motive power, possibly including amendments to account for signals that were not previously included in the communication standards, such as battery state of charge.

Gaps:

- Interface and interoperability standards for mechanical, electrical, control connections between motive power vehicles and on-board subsystems.
- Processes to allow operation of ZE motive power vehicles across the North American railway network.

5.1.1.2 Emergency Response

The hazards associated with ZE rail propulsion technologies differ from those associated with diesel-powered rail vehicles. To mitigate these hazards, first and second responders to incidents involving ZE rail vehicles will need adequate training and equipment to safely respond to and manage hazards. Interested parties discussed the different responses that may be required when encountering different technologies during an incident. For example, fires involving diesel, hydrogen, or batteries may all need to be addressed differently. Automotive standards exist for emergency responders for EVs (e.g., SAE J2990) and for hydrogen vehicles (e.g., SAE J2990/1); however, new standards may need to be created specifically for rail applications due to the increased amount of on-board energy storage and the possibility that rail-specific equipment may differ in chemistry, state, or storage mode, or have different safety mechanisms installed compared to equipment commonly employed in the automotive sector.

In addition to standards relating to emergency response, alignment with existing hazard symbols and markings is needed. Should new symbols or markings be required for rail-specific ZE equipment, existing reference manuals and standards pertaining to hazard recognition will also need to be updated to incorporate ZE rail-specific additions.

Gaps:

- ZE rail propulsion technologies present unique hazards that differ from traditional diesel rail vehicles, requiring specialized training for first responders.
- Current hazard symbols, markings, and reference materials don't include ZE rail-specific indications.

5.1.2 Infrastructure-Specific Codes and Standards

5.1.2.1 Maintenance Facilities

Maintenance facilities are typically enclosed spaces and thus represent a unique challenge when being used with ZE technologies. For example, enclosed spaces pose the hazard of hydrogen accumulation if housing hydrogen-powered vehicles and overheating hazards in the case of battery-powered vehicles. Standards addressing the design, operation, and organization of maintenance facilities, as well as requirements on fuelling and charging infrastructure and other equipment are needed to address technology-specific challenges (e.g., ventilation system performance, sparkless tooling, electrical components, climate control).

Hydrogen vehicles may need to be partially or fully de-fuelled prior to entering the facility, especially if the facility has not been designed or upgraded to accommodate hydrogen vehicles, or prior to certain maintenance operations being performed. De-fuelling may need to happen at a certain distance from the maintenance operations, as some mechanical maintenance work could result in ignition sources. The vehicles must then be refuelled upon completion of the work, which may also have to happen some distance from the maintenance operations. Appropriate setback distances between fuelling and maintenance facilities should be addressed by new or updated standards.

Ventilation in maintenance facilities must also be considered to prevent any potentially dangerous hydrogen concentration within them in case hydrogen-powered vehicles would have leaks, an equipment malfunction, or a designed response to other hazards (e.g., vehicle external fire) among other possibilities. Interested parties noted that older maintenance facilities had significant ventilation systems in place for diesel exhaust since operating locomotives within the facilities was commonplace. Modern practices involve using other vehicles to maneuver locomotives into and out of maintenance facilities, reducing the level of ventilation needed. Therefore, existing ventilation systems designed for diesel equipment are likely not sufficient to safely accommodate hydrogen vehicles and may require upgrades. ZE rail vehicles have a unique advantage in this regard compared to diesel-only as they can be operated on battery power within the facility and as such may not necessarily require shuttling equipment. However, the batteries and the state of charge allowed while the vehicle is in a maintenance facility should also be addressed by standards. As with hydrogen, the batteries may need to be discharged before the vehicle is permitted to enter the facility.

NFPA 2 addresses maintenance facilities for vehicles using compressed hydrogen gas as a fuel. Note that this is not a rail-specific document; however, the key concepts are similar. The chapter of this standard addressing maintenance facilities specifically states that it does not apply to vehicles using cryogenic liquid hydrogen. Existing standards for handling cryogenic liquids and cryogenic hydrogen would have to be reviewed and adapted to be applicable to the rail environment.

As hydrail technology evolves, existing standards that cater to its specific safety requirements, particularly for the operation of maintenance facilities, may have to be adapted or new standards developed. A focus on mitigating the risks associated with hydrogen handling and ensuring the safe operation of these facilities should guide this ongoing work.

Similarly, battery maintenance or storage facilities may require temperature monitoring and control systems, leak detection and ventilation systems, and fire suppression systems specific to the battery chemistries employed and tailored to the expected size and capacity necessary for rail. There may need to be upgrades to fire suppression systems for hydrogen or battery. For example, activation of a water-based sprinkler system may not be appropriate for a battery or electrical fire.

Gaps:

- Specific design and operational standards tailored to the unique challenges of ZE technologies within enclosed maintenance facilities.
- Standards focusing on the prevention of hydrogen accumulation and the unique overheating risks associated with battery-powered vehicles.
- Guidelines outlining procedures for the de-fuelling of hydrogen vehicles or battery discharging prior to entry, including safe distances between fuelling and maintenance activities.
- Guidelines for upgrading older facilities designed primarily for diesel-powered rolling stock to accommodate hydrogen- and battery-powered rolling stock.
- Rail-specific safety and operational standards for vehicles using cryogenic liquid hydrogen.
- Comprehensive safety protocols for battery maintenance facilities that encompass temperature controls, leak detection, and specialized fire suppression systems tailored to the battery chemistries in rail settings.
- Standards that address appropriate fire suppression methodologies for ZE technologies, emphasizing how they differ from traditional systems.

5.1.2.2 Hydrogen Refuelling

The scale of energy requirements, discussed in the Section 3.1, also applies to rail vehicles powered by hydrogen. An HFC-powered class 8 semi truck using compressed hydrogen storage has tanks for approximately 59 kg of hydrogen [73]. In comparison, prototype hydrogen-powered switcher locomotives reportedly store up to 175 kg of hydrogen, and multiple unit passenger trains have storage for up to 260 kg of hydrogen [74]. Larger, heavier trains, especially freight trains operating on long routes, will require significantly more hydrogen fuel and could potentially benefit from tender cars to increase the fuel capacity, which themselves present a gap area as discussed in Section 5.1.3.3.

Existing hydrogen refuelling stations are not able to achieve fuelling rates that are comparable to diesel. Discussions with interviewees suggested that this may not be a practical solution to overcoming this challenge, for example in passenger multiple units, included connecting multiple dispensers to the vehicle along with several hydrogen storage subgroups (e.g., on each vehicle). This may not be a practical solution for larger deployment of the technology, especially for the large hydrogen quantities needed in long-distance rail applications. Large-scale hydrogen refuelling is therefore a gap that could be addressed by standards, including topics such as monitoring on-board tank temperature and communication with the hydrogen refuelling station to safely achieve larger-scale energy transfer.

As discussed in Section 4.2.2.2, numerous standards exist that address hydrogen refuelling stations and

systems. Many of these are specific to automotive applications (e.g., SAE J2600, SAE J2799). Interested parties suggested that existing hydrogen refuelling equipment is frequently out-of-service or that refuelling processes can be unreliable, resulting in interrupted, slow, partial fills. This highlight is an area for potential improvement. Their concerns aligned with California hydrogen refuelling station availability data published by the California Air Resources Board (CARB), which showed that fuelling station availability between the first quarter of 2021 and the second quarter of 2022 ranged from a low of 31% to a high of 95%, with quarterly averages in the range of 58% to 79% [75]. As such, beyond addressing the need for higher-capacity fuelling stations, improvements in reliability and performance may also be required to fulfil the needs of rail operators and promote adoption of hydrogen as a motive fuel in the rail industry.

Discussions with industry experts revealed the need to update or create new standards specifically for hydrogen fuelling of rail applications. These new or updated standards would need to address the design, systems, and controls, such as nozzles, sensors, and communications, of suitable scale for the fuelling rates and quantities required by rail applications for the different hydrogen storage technologies, including compressed gas at various pressures, liquid, cryo-compressed, and metal hydrides.

Gap: Standards addressing the design, testing, and performance of hydrogen fuelling stations, dispensers, subsystems, and on-board fuel systems scaled to the quantities required for long-haul rail operations.

5.1.2.3 Battery Charging

Using traditional fuels, transporting goods by rail can be up to five times more energy-efficient than transporting by truck [76]. Despite their efficiency advantages in relation to other transportation modes, rail vehicles still require large quantities of energy to move due to their large masses. For comparative purposes, a full-size electric North American pick-up truck has a 98 to 131 kWh battery pack [77] and a class 8 semi truck has up to 733 kWh of batteries [78]. These are an order of magnitude smaller than currently published specifications for battery locomotives, which range from 2,400 kWh [11] to 14,500 kWh [12].

Higher-capacity batteries require more powerful chargers to be able to charge in a practical amount of time, such that charging does not affect the service or usefulness of the battery rail vehicle. In addition to the need for higher-powered chargers, the physical and electrical connections between the vehicle and charging station will need to be designed with rail operations (e.g., interchange of equipment between operators) in mind. For example, a universal connector for rail vehicles would significantly reduce the complexity of adoption amongst freight operators who frequently handle equipment that does not belong to them. The AAR had launched an initiative to define an interoperable charging standard for battery-electric locomotives, but paused the effort in April 2023 citing concerns that it is too soon to define a standard for a technology that has undergone limited testing in real-world conditions [68].

Beyond the need for higher-powered versions of the plug-in charging systems common to the automotive industry, the rail industry is also developing and integrating other forms of charging and means of electrification, such as opportunity fast charging and partially electrified systems. Detroit's QLine streetcar system is just one example of a hybrid battery and overhead catenary-powered vehicle capable of charging in a partially electrified system [18]. Plug-in charging is used overnight in the depot, opportunity charging tops up battery levels while the vehicle is stopped at stations with overhead charge bars, and in areas with overhead electrification installed, battery charging and traction power are provided simultaneously.

New or updated standards will be required to address suitably powerful chargers (e.g., megawatt charging systems as in SAE J3271, currently a work in progress) and their components (e.g., transmission cables), and the types of charging systems employed in rail, such as opportunity charging. Improving charging system reliability and resistance to vandalism (e.g., theft of charging cables from stations) may also need to be addressed in a rail context as these are known issues with existing automotive charging systems [79, 80].

Additional work may be needed to address charging at stations accessible to passengers or pedestrians, and around the vehicles, as well as the potential for

mid-route charging islands or charge bars used in opportunity charging. With respect to the locations of charging infrastructure specifically, proximity to critical infrastructure (e.g., hospitals, pipelines) must also be addressed due to the risk of electromagnetic interference. Existing wayside charging equipment may be sufficiently powered for practical charging times for railway applications.

Gap: Standards addressing the design, testing, and performance of battery charging systems, connectors, ports, and communications scaled to the energy demands required for rail applications.

5.1.3 Vehicle-Specific Codes and Standards

5.1.3.1 Crashworthiness

Crashworthiness and crash testing of rail vehicles using ZE motive power were topics of interest to interviewees. Existing standards cover crashworthiness requirements for locomotives (e.g., AAR S-580, AAR S-5506) and topics such as LNG tenders (e.g., AAR M-1004), but may have limited applicability to both battery- and hydrogen-powered ZE locomotives.

Crashworthiness standards, for vehicles and subsystems, may need to be created or amended to ensure ZE vehicles respond in a sufficiently safe manner in collision scenarios and that the risks unique to ZE motive power are addressed. Vehicle crash performance needs to be understood at the component level and at the vehicle system level (e.g., through destructive vehicle testing). Standards are needed to help address the crashworthiness of individual ZE components and subsystems, the mounting locations and methods for mounted components (e.g., hydrogen tank bundles), and potentially the forces that ZE system components must withstand in collisions. Interviewees discussed crash testing being desired as a basis for these future standards. Existing standards from the automotive industry may not be sufficient due to the higher forces encountered in rail applications combined with higher energy storage requirements (e.g., tens or hundreds of hydrogen storage cylinders in rail applications compared to one to three in automotive applications, and rail batteries with more than 100 times the energy capacity of automotive batteries).

Gaps:

- Rail-specific crashworthiness standards for battery- and hydrogen-powered ZE locomotives.
- Guidelines on mounting and collision resilience for ZE components and subsystems.
- Crash testing standards tailored to the unique energy capacities and forces in rail.

5.1.3.2 Shock and Vibration

Operating in a rail environment exposes vehicle systems and components to shock and vibration loads. These forces may be of lower magnitude and higher frequency than the crash forces addressed in the preceding section. Subject-matter experts emphasized the fact that normal rail operations, including coupling locomotives and cars at permissible speeds, can create shock and vibration loads that exceed those created in other mobile applications (e.g., automotive, heavy duty road vehicles, marine). It was noted that, historically, the use of components from other sectors would often result in inadequate performance, which they attributed to the more frequent and severe shock and vibration loads common in rail environments.

ZE technologies originally designed for use in other mobile applications, including HFCs, hydrogen storage, and batteries, can be scaled to meet the energy storage and power requirements of rail applications, but must also be sufficiently resilient and able to withstand the higher shock and vibration loading that a rail environment poses. Subject-matter experts raised this as a need that could be filled by updating existing standards or developing new standards to cover ZE technologies in the rail context.

IEC 61373 provides insights into the management of shock and vibration. However, North America lacks a counterpart to IEC 61373 that exclusively deals with shock and vibration. The importance of vibration cannot be underestimated, as vibration frequencies can trigger resonance, resulting in catastrophic system failure. The performance and integrity of the components that constitute the fuel supply system, including pressurized fuel lines, valves, and fittings for hydrogen railway vehicles, must be understood to ensure safe and reliable vehicle operation. It is

recommended that inertial measurement devices be used in research to understand the behaviour of hydrogen fuel cell locomotives under vibrational stresses. Similar concepts apply to battery-based systems; however, development in this area is further along and may only require incorporation of the data into existing rail-specific electrical standards.

Gap: Shock and vibration performance requirements for ZE equipment that are specific to the rail environment.

5.1.3.3 Tender Cars

Hydrogen fuel and battery tender cars allow for the extended operation of ZE vehicles, due to the additional range gained through the added on-board energy storage, and provide added flexibility in charging or refuelling times. Tender cars can be especially practical where refuelling and charging opportunities are limited, either by the unavailability of infrastructure or inadequate down-time. Potential uses for tender cars include charging or refuelling while coupled to the trainset, or swapping empty and depleted tender cars for full cars. The time to exchange an empty hydrogen fuel tender or discharged battery tender car for a full or charged one could be lower than the time required to fill the tanks or charge the batteries themselves. By swapping tender cars, the waiting hydrogen or battery tender could be replenished over a longer period or at opportune times, potentially extending the working life of the batteries by charging at lower rates, and introducing the opportunity to charge during periods with lower electricity prices. Reducing required charging or fuelling rates could also result in lower infrastructure costs since slower fuelling and charging equipment is typically less expensive.

The transfer of hydrogen fuel between a tender car and locomotive needs further investigation and standardization, and may require regulatory approval. As the locomotive and tender are separate rail vehicles that can be coupled or de-coupled, they must have connectors for the hoses or pipes to transfer the fuel between them. This introduces a point of failure where a leak could occur while the vehicles are connected. There is also the possibility for fuel leaks during intentional or unintended de-coupling events. Since similar issues had to be solved for LNG tenders, those practices and standards could be a foundation for both compressed gas and liquid hydrogen tenders. Existing standards, such as AAR M-1004, cover fuel tenders; however, as of this writing, do not contain specific provisions for hydrogen or batteries. However, AAR M-1004 does currently contain a reserved chapter for alternate fuels [58].

Existing compressed hydrogen tank sizes are not ideal for the amounts of fuel needed in railway applications. Currently, railway applications would require many tanks, necessitating a significant number of valves, fittings, connectors, and hoses, and thereby introducing many points of potential failure in the system. Especially in the case of tender car applications, standardization of larger tank sizes and supporting components (e.g., valves, hoses, mounting structures) is needed. The need for multiple compressed hydrogen gas cylinders for rail applications can already be observed in existing hydrogen-powered multiple units and locomotive trials. The use of hundreds of battery cells and modules in rail applications is similar to what is done in the automotive sector, although at a significantly larger scale, and may require different standards.

Booster units (called B Units; a concept that has been used with diesel locomotives) could also be employed with either hydrogen or battery power. B Units have their own energy storage and traction motors, but no cab. They rely on commands from a connected locomotive with a cab (the A Unit) to operate. Since the B Unit uses its own on-board energy, rather than transferring energy to another vehicle, they bypass issues with hydrogen transfer between vehicles. Although there is still the potential for electricity sharing between A and B Units, electricity transfer between units is similar to the common practice of electricity sharing in multiple unit trains. However, safe use of these units may still require standard interfaces, especially relating to control and energy component status (e.g., battery state of charge).

Since the movement of high-voltage electricity between a battery tender and a locomotive is fundamentally similar to the set up of trains using slugs (heavy vehicles with powered axles but no engine) or in multiple unit trains, the transfer of electricity is not necessarily a gap area. However, other topics relating to the use of battery tender cars (e.g., crashworthiness) are in need of standardization.



"For hydrogen to be useful as a fuel, it must be stored such that a practical amount of energy can be stored in a volume available within a rail vehicle."

Gaps:

- Requirements for battery tender cars and hydrogen tender cars, including the connections and communications between vehicles, accounting for the potential for tender refuelling or recharging and tender car swapping.
- Requirements for battery- or hydrogen-powered B Units.
- Requirements for larger hydrogen tanks, including their supporting components, such as valves, hoses, and mounting structures.

5.1.3.4 Alternative Hydrogen Storage

As discussed in Section 3.1.2, for hydrogen to be useful as a fuel, it must be stored such that a practical amount of energy can be stored in a volume available within a rail vehicle. Current rail applications use compressed hydrogen gas systems [74], and standards such as IEC 63341-2 are in development for this technology in rail applications. However, compressed gas is not the only way to increase the density of hydrogen storage. Cryogenic liquid hydrogen is already being used in some non-rail applications, including hydrogen delivery tankers [35] and as a fuel in space applications [81].

Different hydrogen storage methods present distinct risks due to their unique properties and requirements. Liquid hydrogen, which is stored at extremely low temperatures, poses risks like frostbite and over-pressurization due to rapid expansion when warmed [82]. Compressed hydrogen, stored under high pressure, carries risks of explosive decompression and fires, with the additional concern of material fatigue in containment systems over time [83]. Metal hydride storage, while avoiding some of the extreme temperature and pressure conditions, faces challenges in heat management during the absorption and release of hydrogen, as well as issues related to weight, volume efficiency, and potential chemical hazards [84].

Denser hydrogen storage is essential for many rail applications to achieve similar operational practicality to diesel. Rail-specific standards for cryogenic liquid hydrogen on-board storage do not yet exist. The scope of IEC 63341-2 does not cover liquid hydrogen storage. Therefore, new standards will be required for the use of alternative storage methods of hydrogen in rail applications, potentially including methods such as cryogenic liquid, cryo-compressed, or in a metal hydride.

Gap: Requirements for the inclusion of on-board hydrogen storage using chemical or physical storage methods other than compressed gas.

5.1.3.5 Battery Recycling and Disposal

A CSA Group research report previously outlined the lifecycle of Li-ion batteries for EVs and identified standards (e.g., ANSI/CAN/UL 1974, SAE J3071) relevant to battery recycling and repurposing [85]. This report had an automotive focus; however, the critical topics and gaps identified may also apply to the use of Li-ion batteries for rail propulsion, especially given the quantity of precious metals that will be stored within

the much larger rail batteries. However, the battery chemistries used for rail-specific batteries may differ from those typically used in the automotive sector. For example, while NMC is a common chemistry used in the automotive sector, lithium-titanate (LTO) is common in the rail sector. As such, different recycling and disposal practices may be required to address the differences in materials. For the same battery chemistries, the end of useful life may be reached earlier.

Since rail applications may result in more frequent battery charging and discharging cycles than other sectors, the useful life of rail batteries, including those of the same chemistries used in automotive, could be as little as three to five years compared to 10 years or longer in a typical automotive application [86]. Given the shorter lifespan and size, it will be important that these batteries are designed with second-life repurposing and recycling in mind.

Gap: Design requirements for rail batteries that incorporate repurposing, recycling, and disposal requirements specific to rail battery chemistries and sizes.

5.1.3.6 Environmental Exposure (Including Blockage of Vent Lines)

The North American rail system is subject to a variety of weather conditions and temperatures. Infrastructure and rolling stock can be exposed to a wide range of temperatures, as well as wind, airborne dirt and debris, rain, hail, snow, ice, and other atmospheric and weather conditions. Interested parties highlighted the need for standards addressing ZE technology performance in the wide range of weather and temperature conditions in which the rail vehicles will be operating.

Extreme temperatures can cause unforeseen issues to components, such as malfunctions or performance degradation. For example, in hot conditions, PRDs must be functional so that hydrogen systems can effectively vent excess pressure generated by the expansion of warming hydrogen, but must not be triggered by the external temperature alone. In addition, the ventilation system must ensure the vented hydrogen is carried away from the vehicle and released to the environment, which can be threatened in very cold or dusty conditions where ice or dust accumulation can clog ventilation lines. Potential issues in cold conditions include the blockage of vent lines, as HFCs and H-ICEs both produce water or water vapour as an exhaust product that could freeze and block exhausts or vents.

Thermal management of batteries is essential for their safe operation and to increase their ability to reach their operational design life. Overheating protection and appropriate thermal management systems suitable for the rail environment should be developed for defined conditions regardless of the specific thermal management system deployed (e.g., air or liquid cooled, heating). Beyond thermal loading caused by external temperature exposures, requirements may also be needed to address design parameters, such as the placement of batteries within the vehicle (e.g., on the roof compared to inside or beneath the vehicle).

In addition to hazards caused by ambient temperatures, debris in the environment that can block intake and exhaust vents (e.g., animal nests, dust, insects, ice) can also cause performance and safety issues. Appropriate standards for the rail environment regarding air intake systems could be developed.

In general, the ZE technology systems implemented on rail vehicles will need to meet a minimum performance standard to ensure they are sufficiently resilient to withstand exposure to conditions that similar technologies implemented in other applications (e.g., stationary facilities) may be protected from.

Gaps:

- ZE component and system requirements specific to rail operating conditions, including extreme temperatures and conditions involving ice or debris accumulation.
- Battery management system requirements specific to the rail operating environment.

5.1.3.7 Operation in Enclosed Spaces

Freight and passenger services primarily operate outdoors, and occasionally in enclosed spaces such as tunnels, stations, and maintenance facilities. The operation of ZE equipment in enclosed spaces is a topic requiring further research and development, in

addition to codes and standards development, due to the additional hazards presented by ZE technologies and the limited knowledge available to date on best practices for addressing those hazards. This is particularly relevant in the context of unintended events, such as crashes and fires, that could result in the release and accumulation of hydrogen or toxic battery emissions. The use of ZE equipment in a mixed-technology train (e.g., hydrogen and diesel or diesel and batteries) adds additional complexity since each technology has its own unique hazards, mitigation strategies, and appropriate emergency responses.

As discussed in Section 3.1.2.1, hydrogen gas is lighter than air, meaning it will rise if released from a tank or system, whether accidentally or intentionally by a PRD to prevent over-pressurization. When operating in open spaces this is less of a concern unless there is an ignition source adjacent to the hydrogen point of release. With no source of ignition, the hydrogen will rise and dissipate safely in the atmosphere. In an enclosed environment, however, hydrogen cannot dissipate and will concentrate within the contained area, resulting in a potential fire and explosion hazard, or asphyxiation hazard in a small space. Standards will need to address these factors, helping to minimize the potential for hydrogen release in an enclosed space, and requiring ventilation or mitigation measures for hydrogen released in an enclosed space.

Further research and testing may be required to determine the safest responses to incidents involving hydrogen vehicles in enclosed spaces, such as directed release of hydrogen with mitigation against accumulation and other hazards, controlled intentional burn-off, or other strategies. In addition, the sudden release of high-pressure hydrogen gas from a PRD can be loud, a danger potentially exacerbated in an enclosed space. Occupational noise exposure standards exist (e.g., 49 CFR Part 227) that could be referenced for noise limits. Mitigation strategies may require research, development, and testing.

Interested parties noted that in situations where a hydrogen-diesel mixed technology train is travelling through a tunnel, the heat from the diesel exhaust may raise the temperature within the tunnel and lead to the unintended release of hydrogen gas if TPRDs are triggered. This is an additional area where new standards may be necessary to allow for the safe use of trainsets using multiple motive power technologies.

Gaps:

- Research and testing needed to determine vehicle-based equipment and process best practices for mitigating battery- and hydrogen-related hazards in enclosed spaces, which will then inform standard development. This could include component design (e.g., the type, quantity, and location of PRDs on vehicle-mounted hydrogen tanks and their supporting components) and subsystem design (e.g., mounting orientation and mounting location of tanks and batteries within the vehicle).
- ZE technology-specific ignition prevention, ventilation, and fire suppression requirements for infrastructure that includes enclosed spaces, such as stations and tunnels. Some information from NFPA 2 for maintenance garages, which is relevant to smaller quantities in automobiles, may need to be expanded to address larger quantities in rail vehicles.

5.1.3.8 External Hazards

ZE rail vehicles present different challenges to those powered by diesel with respect to exposure to external hazards, including fires, floods, and vandalism. Batteries can be extremely difficult to extinguish once they have ignited and can also re-ignite once extinguished [29]. Hydrogen stored on board rail vehicles, whether as a compressed gas or a cryogenic liquid, will expand and increase in pressure if heated. As discussed previously, PRDs are built into the system to release excess pressure to prevent damage to the system. This presents a separate issue, however, when the heat source causing the PRD to vent hydrogen is also an ignition source, such as a fire adjacent to the vehicle. The release of hydrogen into an existing fire could exacerbate the situation, resulting in a larger fire or a jet of flame from the vehicle. Design standards can help ensure that ZE rail vehicles are sufficiently resistant to the heat caused by external fires. Existing standards may not be sufficient or may need to be expanded to cover ZE equipment (e.g., NFPA 130 regarding floor fire resistance of passenger

rail equipment). Finally, regulations like TC's Railway Locomotive Inspection and Safety Rules [66], which address external hazards such as exposure to fire, may need to be revisited and updated to adequately encompass new zero-emission technologies like hydrogen- or battery-powered systems. Another example of external hazards addressed by US regulations is impacts to windshields and windows (as in 49 CFR Part 223). Existing regulations may need to be adapted or expanded to protect alternative propulsion equipment that is located outside of the body of the vehicle (e.g., on the roof or under the floor).

Gap: ZE technology-specific standards for the design, testing, and performance of on-board energy storage equipment and its ability to withstand external hazards such as impacts from airborne or track-level objects, fires, floods, and vandalism.

5.1.3.9 Unattended Vehicles

In addition to the existing concerns for any unattended rail vehicles regardless of motive power, hydrogen-powered rail vehicles using compressed gas or cryogenic liquid storage methods pose unique challenges. Both systems must incorporate PRDs to release excess pressure to prevent system damage. The PRDs could activate while the vehicle is in operation or while it is parked, unattended. Therefore, fuelled hydrogen rail vehicles should not be left in enclosed spaces, near areas where released hydrogen could collect, or near any potential ignition sources. Updates to existing operational standards for unattended rail vehicles, or new standards specific to the hazards of hydrogen-powered rail vehicles, should be developed.

Gap: Requirements for the safe storage of unattended ZE vehicles, particularly those containing hydrogen.

5.1.3.10 Driver-Vehicle Interface

Current ZE rail vehicle designs incorporate the design principles and layout of existing diesel locomotive cabs. Discussions with interested parties revealed a preference to maintain the current driver control interface used on diesel-powered equipment. This may be motivated by a desire to enhance technology adoption by reducing barriers such as driver retraining. However, there may be aspects of the new propulsion technologies that are not well-suited to existing interface designs, such as the operation of regenerative braking functionality. For example, diesel locomotives have dynamic braking capability (electrical brakes via resistor grids), which can be adapted for regenerative braking, but are not automatically engaged (as is the case in ZE automotive vehicles) and require driver action to engage. Further, some of the conditions of the ZE equipment should likely be displayed to the driver (e.g., battery state of charge, or safety-relevant information such as a PRD activation or overheating battery module). Therefore, additional instrumentation and information displays may be required on ZE vehicles.

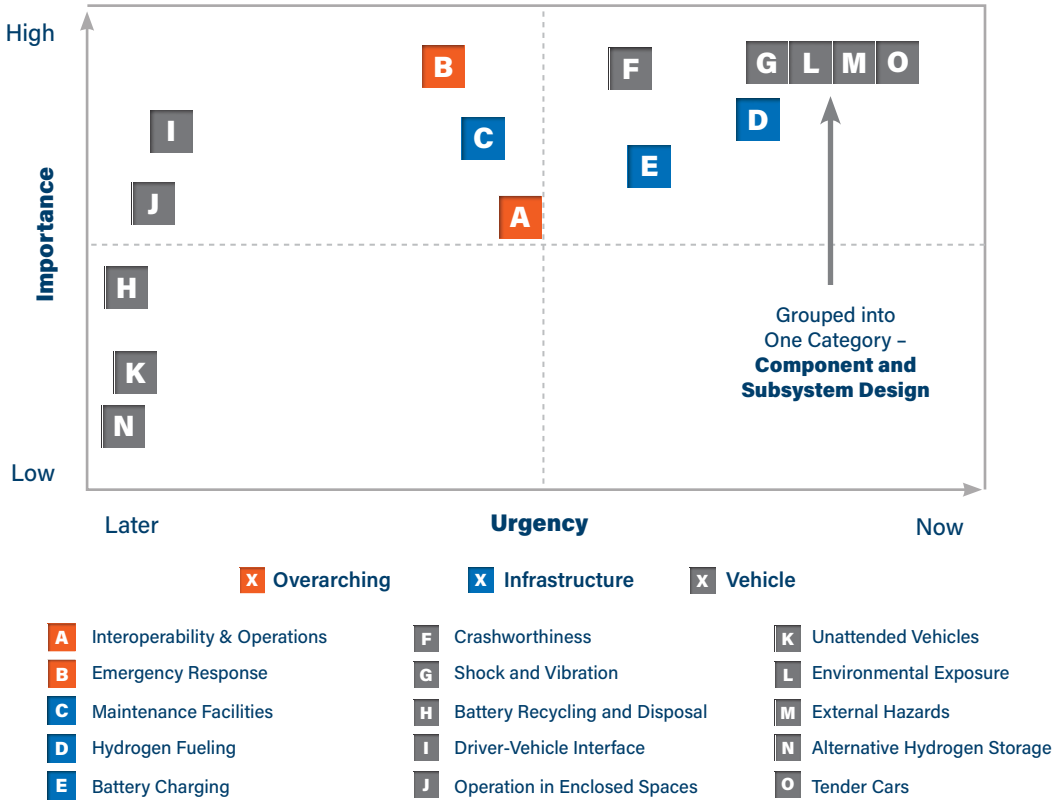
Gap: Standardized driver-vehicle interface, including controls and information displays relevant to ZE equipment, such as regenerative braking control and battery state-of-charge information.

5.2 Roadmap to Advancing ZE Propulsion

The preceding sections outlined the importance of ZE propulsion technologies for rail in helping Canada and the US meet their emissions targets, as well as areas where the existing codes and standards do not provide sufficient coverage. It follows then, that codes and standards will need to be created or updated to provide the necessary coverage to support the implementation of ZE propulsion technologies in rail applications. The development of appropriate codes and standards is not a trivial task; it requires time and resources. Since each gap identified in Section 5.1 may be addressed simultaneously, the gaps have been prioritized based on their impact on the implementation of ZE propulsion technologies for rail.

The gap areas identified by the presented research, including consultation with interested parties, workshop participation, and survey responses, were rated for both their importance and urgency with respect to their impact on the implementation of ZE propulsion technologies for rail. Based on this, the gap areas were charted and are presented in Figure 6, below. The positions of the gap areas in the chart are approximate and may differ whether considered in a freight or passenger rail context.

Figure 6: Identified Gap Areas in Existing Codes and Standards Organized by Importance and Urgency



It is important to note that many of the gap areas are related to, or dependent on, other areas. For example, interoperability relies on the standardization of other concepts, such as hydrogen fuelling, battery charging, and control interfaces, to define common designs and practices. Likewise, some gap areas described in Section 5.1 can be grouped more generally here. For example, the shock and vibration, tender cars, exposure to elements and temperature, and design for external hazards gap areas can be grouped as component and subsystem design for the rail environment.

The priority gap areas defined as being of high importance and high urgency are located in the upper right quadrant of Figure 6. Covering these gap areas with new or updated codes and standards would likely have the greatest impact on the implementation of ZE propulsion technologies in a rail context. Discussion on the priority gap areas is presented below.

5.2.1 Component and Subsystem Design for the Rail Environment

A primary concern of interested parties was the lack of ZE technology built to rail-specific standards or designed specifically for the rail operating environment, and the impact this gap has on implementation. With the majority of ZE component and subsystem design stemming from light-duty automotive applications, the comparatively tougher rail environment, scaling in size and performance requirements, and longer operating times are the primary drivers for rail-specific standardization of components and subsystems.

There was a clear desire for rail-specific design of systems, such as HFCs, hydrogen storage and delivery systems, batteries, and tender cars, as well as design requirements such as shock and vibration resistance, exposure to elements and temperature, and resilience against external hazards. This gap area is of particular significance due to the impact it would have on other key gap areas, including crashworthiness and interoperability.

5.2.2 Crashworthiness

Safety is a priority for all railway organizations in North America, and many standards and regulations have been developed to help ensure a safe railway system. For ZE technology to be successfully deployed, safe operation and mitigation of hazards is essential. As discussed in Section 5.1.3.1, existing standards include crashworthiness requirements for locomotives and LNG tender cars. Additionally, to operate in the North American rail system, ZE rail vehicles (both locomotives and multiple units) must meet compliance requirements for each applicable jurisdiction, governed for example by TC and the FRA.

There will be a need for understanding the crashworthiness of ZE rail vehicles, and standards that vehicles can be manufactured to and tested against to ensure compliance. These standards extend to any of the new components, subsystems, and integration into well-established parts of railway vehicles, for example, robustness on impact of battery cells, strings, modules, thermal and energy management, energy storage system, and installation on the railway vehicle. Expansion and adaption of crashworthiness standards to new ZE technology is important for successful implementation. For example, the structural requirements for underfloor mounted diesel tanks could potentially be adapted to include structural requirements for underfloor mounted batteries or hydrogen storage. Conversely, if these systems were installed in different locations (e.g., the long-hood), the standard could be amended. Similarly, the structural requirement for LNG tender cars could be applied to ZE technologies. In some cases, completely new standards may need to be developed to meet the stringent safety expectations of railways, industry, and regulators.

5.2.3 Hydrogen Refuelling

As discussed in Section 5.1.2.2, the combination of large energy storage capacity requirements and short time slots for fuelling to enable similar and efficient use of motive power requires high-capacity fuelling systems. While it is possible to build and fuel initial prototype vehicles and fleets with less-demanding operations using technology designed for other applications, such as buses or heavy-duty trucks, series production hydrail vehicles would benefit from dedicated hydrogen fuelling technology.

Hydrogen fuelling standards could help increase adoption of hydrail. Without such standards, there's a risk of incompatibility among hydrail vehicles from different railroads or manufacturers, due to varying refuelling systems. This lack of uniformity could make it challenging to share or scale these vehicles, thereby obstructing their interoperability. These standards could also prevent forced early obsolescence of the initial generation of hydrail vehicles, if the standards are suitably robust so that the fuelling systems remain unchanged for a significant time. Fuelling standardization could cover different on-board storage systems, such as compressed gas and liquid, for a variety of rail sector applications (e.g., long-distance freight, commuter, light rail).

5.2.4 Battery Charging

Like hydrogen fuelling, battery charging in a rail context, as discussed in Section 5.1.2.3, will require more powerful systems than currently exist for other applications, such as heavy-duty trucks. Standardized charging systems can provide similar benefits to standardized hydrogen fuelling systems, by aiding interoperability and enlarging the potential network for use of a battery electric rail vehicle. Likewise, these standards could help prevent obsolescence or significant retrofits of early generation battery electric rail vehicles by ensuring their compatibility with future charging systems due to the stability afforded by standards. An additional benefit could be that various on-board battery chemistries could be safely accommodated by the same charger, or that mechanical and electrical interfaces of a charger could work with

motive power vehicles from different manufacturers, similar to ongoing developments in charger compatibility occurring in the automotive sector.

5.2.5 Interoperability

Interoperability was not included in the upper right quadrant of Figure 6; however, the research and consultation with interested parties indicated that it will be a key consideration in the implementation of ZE rail propulsion technologies, especially in a freight rail context. The primary reason for not including interoperability in the upper right quadrant was that, as previously explained, interoperability relies on the standardization of other areas. Thus, by standardizing hydrogen fuelling or battery charging and driver-vehicle interfaces, for example, interoperability becomes built into the system. Given that, especially in a freight context, motive power vehicles are frequently operated over railway networks other than those of their owners to enable efficient asset utilization. As such, interoperability is key for successful rail network-wide implementation of ZE technology.

6 Conclusions

ZE technologies are undergoing rapid advancement and implementation across a range of industries and use cases and will play a pivotal role in global decarbonization efforts. While these technologies are more developed in certain sectors, such as automotive and stationary power supply, their application in a rail-specific context and operating environment has been limited to date. To meet the needs of the North American rail industry, ZE propulsion technologies must be able to operate safely and reliably in extreme climates, fluctuating temperatures, in larger formats than what has been used in automotive applications, and with more hazards than what is expected in stationary applications. Large, powerful, and robust systems are required to handle the sheer energy needs of a railway vehicle, and the supporting infrastructure for those vehicles will need to change to accommodate the newer technologies. As such, this report identified gaps in the existing codes and standards landscape applicable to the overarching railway system and to the infrastructure and vehicles specifically.

Safety is of paramount importance and is a priority in all aspects of railway operation, and was therefore the central theme of gaps specific to the railway operating environment. Beyond the need to ensure safe operations in all environments (e.g., within stations, facilities, tunnels), design and interoperability of equipment and infrastructure (from the system-level down to the individual sub-component), refuelling and charging, emergency response, and operational processes were identified as areas in need of rail-specific codes and standards definition.

As pilot prototype vehicles with ZE technologies emerge within the North American rail market, it is likely that these technologies will soon become part of the rail operating environment. To advance the use of these technologies and ease the transition away from traditional fuels, a methodical and organized approach to the development of rail-specific ZE technology standards is needed.

Based on how each of the identified gaps in the existing codes and standards landscape relates to the development, implementation, and eventual adoption of the technologies within the rail sector, each gap was rated for its relative importance and urgency. Since ZE pilot vehicle implementation and proof-of-concept operations have already begun, component and subsystem design specific to the rail environment is rated as a high priority amongst the identified gaps. The design of components and subsystems, including within the vehicle, charging and refuelling equipment, and critical supporting infrastructure must be specified to help ensure safe and reliable operation in a rail context. By addressing these critical gaps, ZE propulsion technologies may be more likely to gain interest from the market and acceptance from regulators. Additionally, well-designed components and subsystems can ease the development of codes and standards relating to the other critical gap areas: crashworthiness, fuelling/charging, and interoperability.

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Appendix A – Survey Questions

Survey Questions

1. The following topics have been identified as areas relating to the use of hydrogen or battery electrification in a rail environment that may require further standardization work. Please rate the following areas on how impactful you believe the development of codes and standards would be on the advancement and adoption of these technologies within the rail industry (score between low and high; scrolling across the screen may be required to see all scoring options):
   - Crash worthiness
   - Shock and vibration
   - Maintenance and inspection
   - Hydrogen fuel or battery tenders
   - Programmable systems
   - Liquid hydrogen fuel
   - Interfaces: vehicle – infrastructure
   - Diesel – hydrogen or hydrogen combustion engines
   - Other (please specify in question 3)
2. Rank the following areas by priority for development of codes and standards for advancing hydrogen and battery electrification technologies in the rail sector, with highest being first and lowest being last:
   - Crash worthiness
   - Shock and vibration
   - Maintenance and inspection
   - Hydrogen fuel or battery tenders
   - Programmable systems
   - Liquid hydrogen fuel
   - Interfaces: vehicle – infrastructure
   - Diesel – hydrogen or hydrogen combustion engines
   - Other (please specify in question 3)
3. Are you aware of other gaps in the existing codes and standards pertaining to hydrogen or battery electrification in rail applications that were not included in the preceding questions? If so, please describe them below.
4. If you would like to further discuss gaps or prioritization of codes and standards relating to hydrogen and battery electrification in the rail sector with our team, please provide your name and contact information below. Your responses will remain anonymous with respect to the final report.

Interview format:

Interview questions were tailored to the individual based on their areas of expertise. In general, introductory questions were asked, with follow-up questions where appropriate, and open-ended questions were favoured. The interviews were intended to be conversational.

Appendix B – Applicable Documents and Regulations

Table B-1: Applicable Documents

Designation	Title	Publication Year	Publisher	Topic
Association of American Railroads (AAR)				
AAR S-580	Locomotive Crashworthiness Requirements, S-580	2020	AAR	Vehicle
AAR S-5506	Performance Requirements for Diesel Electric Locomotive Fuel Tanks, S-5506	2001	AAR	Vehicle
AAR M-1004	Interoperable Fuel Tenders for Locomotives, M-1004	2023	AAR	Vehicle
AAR M-1005	Interoperable Battery Tenders for Locomotives, M-1005	2022	AAR	Vehicle
American Public Transit Association (APTA)				
APTA PR-CS-S-007-98	Fuel Tank Integrity on Non Passenger Carrying Locomotives	2004	APTA	Vehicle
APTA PR-CS-S-034-99	Design and Construction of Passenger Railroad Rolling Stock	2023	APTA	Vehicle
American Society of Mechanical Engineers (ASME)				
ASME B31.12	Hydrogen piping and pipelines	2008	ASME	Overarching
ASME BPVC	Boiler and pressure vessel code	2023	ASME	Overarching
ASME STP-PT-006	Design guidelines for hydrogen piping and pipelines	2007	ASME	Overarching
ASME RT-1	Safety Standard for Structural Requirements for Light Rail Vehicles and Streetcars	2020	ASME	Vehicle
ASME RT-2	Safety Standard for Structural Requirements for Heavy Rail Transit Vehicles	2021	ASME	Vehicle
ASME STP/PT-005	Design Factor Guidelines for High-Pressure Composite Hydrogen Tanks	2006	ASME	Vehicle
ASME STP/PT-017	Properties for Composite Materials in Hydrogen Science	2008	ASME	Vehicle
ASME STP/PT-023	Guidelines for In-Service Inspection of Composite Pressure Vessels	2009	ASME	Vehicle

Designation	Title	Publication Year	Publisher	Topic
American Society for Testing and Materials (ASTM)				
ASTM B577	Standard test methods for detection of cuprous oxide (hydrogen embrittlement susceptibility) in copper	2019	ASTM	Overarching
ASTM E2652	Standard test method for assessing combustibility of materials using a tube furnace with a cone-shaped airflow stabilizer, at 750°C	2009	ASTM	Overarching
ASTM F1459	Standard test method for determination of the susceptibility of metallic materials to hydrogen gas embrittlement (HGE)	2006	ASTM	Overarching
ASTM F1624	Standard test method for measurement of hydrogen embrittlement threshold in steel by the incremental step loading technique	2012	ASTM	Overarching
ASTM F519	Standard test method for mechanical hydrogen embrittlement evaluation of plating/coating processes and service environments	2018	ASTM	Overarching
ASTM G142	Standard test method for determination of susceptibility of metals to embrittlement in hydrogen containing environments at high pressure, high temperature, or both	1998	ASTM	Overarching
ASTM D 7606	Standard Practice for Sampling of High Pressure Hydrogen and Related Fuel Cell Feed Gases	2017	ASTM	Overarching
Bureau de normalisation du Québec (BNQ)				
CAN/BNQ 1784-000	Canadian Hydrogen Installation Code	2022	BNQ	Overarching
British Standards Institution (BSI)				
EN 17127	Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols	2020	BSI	Infrastructure
EN 17124	Hydrogen fuel – Product specification and quality assurance for hydrogen refuelling points dispensing gaseous hydrogen – Proton exchange membrane (PEM) fuel cell applications for vehicles	2022	BSI	Overarching
EN 50122-1	Railway applications. Fixed installations. Electrical safety, earthing and the return circuit Protective provisions against electric shock	2022	BSI	Infrastructure
EN 50122-2	Railway applications - Fixed installations – Electrical safety, earthing and the return circuit – Part 2: Provisions against the effects of stray currents caused by DC traction systems	2023	BSI	Infrastructure
EN 50122-3	Railway applications. Fixed installations. Electrical safety, earthing and the return circuit Mutual Interaction of AC and DC traction systems	2022	BSI	Infrastructure
Compressed Air and Gas Institute (CAGI)				
CAGI 3075	B19.1 Safety standards for compressor systems	2011	CAGI	Infrastructure

Designation	Title	Publication Year	Publisher	Topic
Compressed Gas Association (CGA)				
CGA C-6.4	Methods for External Visual Inspection of Natural Gas Vehicle (NGV) and Hydrogen Gas Vehicle (HGV) Fuel Containers and Their Installations	2007	CGA	Vehicle
CGA G-5	Hydrogen	2017	CGA	Overarching
CGA G-5.3	Commodity Specification for Hydrogen	2017	CGA	Overarching
CGA G-5.4	Standard for Hydrogen Piping Systems at User Locations	2019	CGA	Infrastructure
CGA G-5.5	Standard for Hydrogen Vent Systems	2021	CGA	Overarching
CGA G-5.6	Hydrogen Pipeline Systems	2005	CGA	Infrastructure
CGA H-14	HYCO Plant Gas Leak Detection and Response Practices	2018	CGA	Infrastructure
CGA H-3	Standard for Cryogenic Hydrogen Storage	2019	CGA	Infrastructure
CGA H-4	Terminology Associated with Hydrogen Fuel Technologies	2020	CGA	Overarching
CGA H-5	Standard for Bulk Hydrogen Supply Systems (an American National Standard)	2020	CGA	Infrastructure
CGA P-1, CGA P-1-OSHA	Standard for Safe Handling of Compressed Gases in Containers	2022	CGA	Overarching
CGA P-11	Guideline for Metric Practice in the Compressed Gas Industry	2019	CGA	Overarching
CGA P-12	Guideline for Safe Handling of Cryogenic and Refrigerated Liquids	2023	CGA	Overarching
CGA P-19	CGA Recommended Hazard Ratings for Compressed Gases	2019	CGA	Overarching
CGA P-22	Guideline for the Responsible Management and Disposition of Compressed Gases and their Cylinders	2021	CGA	Overarching
CGA P-28	OSHA Process Safety Management and EPA Risk Management Plan Guidance Document for Bulk Liquid Hydrogen Supply Systems	2022	CGA	Infrastructure
CGA P-41	Locating Bulk Liquid Storage Systems in Courts	2023	CGA	Infrastructure
CGA P-56	Cryogenic Vaporization Systems—Prevention of Brittle Fracture of Equipment and Piping	2022	CGA	Overarching
CGA P-59	Prevention of Excessive Pressure During Filling of Cryogenic Vessels	2015	CGA	Overarching
CGA P-6	Standard Density Data, Atmospheric Gases and Hydrogen	2012	CGA	Overarching
CGA P-60	Guideline for the Use of the North American Industrial Classification System and the Standard Industrial Classification Indices	2021	CGA	Overarching

Designation	Title	Publication Year	Publisher	Topic
CGA P-68	Standard for Roadside Inspections of Vehicles Transporting Class 2 Hazardous Materials (formerly CGA SB-40)	2016	CGA	Vehicle
CGA P-69	Guideline for Emergency Response to Cryogenic Liquid Releases	2018	CGA	Overarching
CGA P-82	Standard for Maintenance of Transfer Hoses	2019	CGA	Overarching
CGA P-88	Guideline for the Maintenance of Bulk Delivery Equipment Containing Class 2 Hazardous Materials (Formerly SB-41)	2020	CGA	Vehicle
CGA PS-28	CGA Position Statement on Non-ASME Certified Pressure Relief Valves Used for Thermal Expansion Relief in Certain Piping Systems	2019	CGA	Overarching
CGA PS-31	CGA Position Statement on Cleanliness for Proton Exchange Membranes Hydrogen Piping/Components	2007	CGA	Overarching
CGA PS-33	CGA Position Statement on Use of LPG or Propane Tank as Compressed Hydrogen Storage Buffers	2008	CGA	Infrastructure
CGA PS-43	CGA Position Statement on Selection of Pressure Relief Devices for Tubes	2016	CGA	Overarching
CGA PS-46	CGA Position Statement on Roofs Over Hydrogen Storage Systems	2017	CGA	Overarching
CGA PS-48	CGA Position Statement on Clarification of Existing Hydrogen Setback Distances and Development of New Hydrogen Setback Distances in NFPA 55	2016	CGA	Infrastructure
CGA PS-55	CGA Position Statement on Use of Nonsparking Tools	2019	CGA	Overarching
CGA PS-69	CGA Position Statement on Liquefied Hydrogen Supply System Separation Distances	2022	CGA	Infrastructure
CGA S-1.1	Pressure Relief Device Standards-Part 1-Cylinders for Compressed Gases	2011	CGA	Overarching
CGA S-1.2	Pressure Relief Device Standards-Part 2-Portable Containers for Compressed Gases	2009	CGA	Vehicle
CGA S-1.3	Pressure Relief Device Standards-Part 3-Stationary Storage Containers for Compressed Gases	2020	CGA	Infrastructure
Canadian General Standards Board (CGSB)				
CAN/CGSB-43.147	Containers for transport of dangerous goods by rail	2023	CGSB	Vehicle
CAN/CGSB-43.149	Ton Containers for the Transportation of Dangerous Goods	2023	CGSB	Overarching

Designation	Title	Publication Year	Publisher	Topic
Canadian Standards Association (CSA Group)				
ANSI/CAN/CSA/ ISO 12617	Road vehicles – Liquefied natural gas (LNG) refuelling connector – 3,1 MPa connector	2015	CSA	Infrastructure
ANSI/CSA CHMC 1	Test methods for evaluating material compatibility in compressed hydrogen applications – Metals	2014	CSA	Overarching
ANSI/CSA CHMC 2	Test methods for evaluating material compatibility in c ompressed hydrogen applications – Polymers	2019	CSA	Overarching
ANSI/CSA FC 3	Portable Fuel Cell Power Systems	2004	CSA	Overarching
ANSI/CSA HGV 4.5	Priority and sequencing equipment for hydrogen vehicle fueling stations	2013	CSA	Infrastructure
ANSI/CSA HGV 4.6	Manually operated valves for use in gaseous hydrogen vehicle fueling stations	2013	CSA	Infrastructure
CAN/CSA-C22.2 NO. 60079-0	Explosive Atmospheres – Part 0: Equipment – General Requirements	2015	CSA	Overarching
CAN/CSA-C22.2 NO. 60079-7	Explosive Atmospheres – Part 7: Equipment Protection by Increased Safety 'e'	2016	CSA	Overarching
CAN/CSA-C22.2 NO. 60079-11	Explosive Atmospheres – Part 11: Equipment Protection by Intrinsic Safety "i"	2014	CSA	Overarching
CAN/CSA-C22.2 NO. 60079-15	Explosive atmospheres – Part 15: Equipment protection by type of protection "n"	2016	CSA	Overarching
CSA 60079-40	Explosive Atmospheres – Part 40: Requirements for process sealing between flammable process fluids and electrical systems	2020	CSA	Overarching
CSA B51	Boiler, pressure vessel, and pressure piping code	2019	CSA	Overarching
CSA B72	Installation code for lightning protection systems	2020	CSA	Overarching
CSA B108.1	Compressed natural gas refuelling stations installation code	2021	CSA	Infrastructure
CSA B108.2	Liquefied natural gas refuelling stations installation code	2021	CSA	Infrastructure
CSA B109.1	Compressed natural gas vehicle installation code	2021	CSA	Vehicle
CSA B109.2	Liquefied natural gas vehicle installation code	2021	CSA	Vehicle
CSA B401.1	Natural gas vehicle (NGV) maintenance facilities code	2021	CSA	Infrastructure
CSA B401.2	Propane vehicle maintenance facilities code	2021	CSA	Infrastructure
CSA C22.1	Canadian electrical code, Part I (25th Edition), Safety standard for electrical installations	2021	CSA	Overarching

Designation	Title	Publication Year	Publisher	Topic
CSA C22.2 No. 0.4	Bonding of electrical equipment	2017	CSA	Overarching
CSA C22.2 No. 0.17	Evaluation of properties of polymeric materials	2022	CSA	Overarching
CSA C22.2 No. 14	Industrial control equipment	2018	CSA	Overarching
CSA C22.2 No. 94.1	Enclosures for electrical equipment, non-environmental considerations (Tri-national standard with NMX-J-235/ 1-ANCE-2015 and UL 50)	2015	CSA	Overarching
CSA C22.2 No. 94.2	Enclosures for electrical equipment, environmental considerations (Trinational standard with NMX-J-235/ 2-ANCE-2020 and UL 50E)	2020	CSA	Overarching
CSA C22.2 No. 107.1	Power conversion equipment	2016	CSA	Overarching
CSA C22.2 No. 139	Electrically operated valves	2019	CSA	Overarching
CSA C22.2 No. 286	Industrial control panels and assemblies	2017	CSA	Overarching
CSA C22.2 No. 301	Industrial electrical machinery	2016	CSA	Overarching
CSA C22.2 No. 2556	Wire and cable test methods (Trinational standard with NMX-J-556-ANCE-2021 and UL 2556)	2021	CSA	Overarching
CSA C22.2 No. 60079-1	Explosive atmospheres – Part 1: Equipment protection by flameproof enclosures "d"	2016	CSA	Overarching
CSA C22.2 No. 60079-2	Explosive atmospheres – Part 2: Equipment protection by pressurized enclosure "p"	2016	CSA	Overarching
CSA C22.2 No. 60079-5	Explosive Atmospheres – Part 5: Equipment protection by powder filling 'q'	2016	CSA	Overarching
CSA C22.2 No. 60079-6	Explosive atmospheres – Part 6: Equipment protection by liquid immersion 'o'	2017	CSA	Overarching
CSA C22.2 No. 60079-13	Explosive atmospheres – Part 13: Equipment protection by pressurized room "p" and artificially ventilated room "v"	2019	CSA	Overarching
CSA C22.2 No. 60079-25	Explosive atmospheres – Part 25: Intrinsically safe electrical systems	2022	CSA	Overarching
CSA C22.2 No. 60079-29-1	Explosive atmospheres – Part 29-1: Gas detectors – Performance requirements of detectors for flammable gases	2017	CSA	Overarching
CSA C22.2 No. 60079-29-4	Explosive atmospheres – Part 29-4: Gas detectors – Performance requirements of open path detectors for flammable gases	2016	CSA	Overarching
CSA C22.2 No. 60079-46	Explosive atmospheres – Part 46: Equipment assemblies	2019	CSA	Overarching

Designation	Title	Publication Year	Publisher	Topic
CSA C22.2 No. 60079-47	Explosive atmospheres – Part 47: Equipment protection by 2-wire intrinsically safe Ethernet concept (2-WISE)	2022	CSA	Overarching
CSA C22.2 No. 60529	Degrees of protection provided by enclosures (IP Code)	2016	CSA	Overarching
CSA C22.2 No. 62282-2	Fuel cell technologies Part 2: Fuel cell modules	2018	CSA	Overarching
CSA C61000-3-11	Electromagnetic compatibility (EMC) – Part 3-11: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems – Equipment with rated current ≤75 A and subject to conditional connection	2021	CSA	Overarching
CSA C61000-4-1	Electromagnetic compatibility (EMC) – Part 4-1: Testing and measurement techniques – Overview of the IEC 61000-4 series	2019	CSA	Overarching
CSA E60730-2-14	Automatic electrical controls – Part 2-14: Particular requirements for electric actuators	2020	CSA	Overarching
CSA E60730-2-15	Automatic electrical controls for household and similar use – Part 2-15: Particular requirements for automatic electrical air flow, water flow and water level sensing controls	2014	CSA	Overarching
CSA E61959	Secondary cells and batteries containing alkaline or other non-acid electrolytes – Mechanical tests for sealed portable secondary cells and batteries	2014	CSA	Overarching
CSA E62660-1	Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 1: Performance testing	2021	CSA	Vehicle
CSA E62660-2	Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 2: Reliability and abuse testing	2021	CSA	Vehicle
CSA HPIT 1	Compressed hydrogen powered industrial truck on-board fuel storage and handling components	2015	CSA	Vehicle
CSA HPIT 2	Dispensing systems and components for fueling hydrogen powered industrial trucks	2017	CSA	Vehicle
CSA ISO 3100	Risk management – Guidelines	2018	CSA	Overarching
CSA SPE-2.1.3	Best practices for defueling, decommissioning, and disposal of compressed hydrogen gas vehicle fuel containers	2020	CSA	Vehicle
CSA SPE-343	Electric vehicle energy management systems	2021	CSA	Vehicle
CSA TS-602	Railway applications – Rolling stock – Onboard lithium-ion traction batteries	2023	CSA	Vehicle
CSA Z246.2	Emergency preparedness and response for petroleum and natural gas industry systems	2018	CSA	Overarching
CSA Z276	Liquefied natural gas (LNG) – Production, storage, and handling	2022	CSA	Infrastructure
CSA Z767	Process safety management	2017	CSA	Overarching

Designation	Title	Publication Year	Publisher	Topic
CSA/ANSI CHMC 2	Test methods for evaluating material compatibility in compressed hydrogen applications – Polymers	2019	CSA	Overarching
CSA/ANSI B22734	Hydrogen generators using water electrolysis – Industrial, commercial, and residential applications	2023	CSA	Infrastructure
CSA/ANSI FC 1/ CSA C22.2 NO. 62282-3-100	Fuel cell technologies – Part 3-100: Stationary fuel cell power systems – Safety	2021	CSA	Infrastructure
CSA/ANSI FC 5	Hydrogen generators using fuel processing technologies Part 1: Safety	2021	CSA	Infrastructure
CSA/ANSI HGV 2	Compressed hydrogen gas vehicle fuel containers	2021	CSA	Vehicle
CSA/ANSI HGV 3.1	Fuel system components for compressed hydrogen gas powered vehicles	2022	CSA	Vehicle
CSA/ANSI HGV 4.1	Hydrogen-dispensing systems	2020	CSA	Infrastructure
CSA/ANSI HGV 4.2	Hoses for dispensing compressed gaseous hydrogen	2022	CSA	Infrastructure
CSA/ANSI HGV 4.3	Test methods for hydrogen fueling parameter evaluation	2022	CSA	Overarching
CSA/ANSI HGV 4.4	Gaseous hydrogen – Fuelling stations – Valves	2021	CSA	Infrastructure
CSA/ANSI HGV 4.9	Hydrogen fueling stations	2020	CSA	Infrastructure
CSA/ANSI HGV 4.10	Standard for fittings for use in compressed gaseous hydrogen fueling stations	2021	CSA	Infrastructure
CSA/ANSI HPRD 1	Thermally activated pressure relief devices for compressed hydrogen vehicle (HGV) fuel containers	2021	CSA	Vehicle
CSA/ANSI LNG 3.1	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 1: General requirements and definitions	2022	CSA	Vehicle
CSA/ANSI LNG 3.2	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 2: Performance and general test methods	2022	CSA	Vehicle
CSA/ANSI LNG 3.3	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 3: Check valve	2022	CSA	Vehicle
CSA/ANSI LNG 3.4	Liquefied natural gas (LNG) fuel system components – Part 4: Manual valve	2022	CSA	Vehicle
CSA/ANSI LNG 3.5	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 5: Tank pressure gauge	2022	CSA	Vehicle
CSA/ANSI LNG 3.7	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 7: Pressure relief valve	2022	CSA	Vehicle
CSA/ANSI LNG 3.8	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 8: Excess flow valve	2022	CSA	Vehicle

Designation	Title	Publication Year	Publisher	Topic
CSA/ANSI LNG 3.9	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 9: Gas-tight housing and ventilation hose	2022	CSA	Vehicle
CSA/ANSI LNG 3.10	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 10: Rigid fuel line in stainless steel	2022	CSA	Vehicle
CSA/ANSI LNG 3.11	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 11: Fittings	2022	CSA	Vehicle
CSA/ANSI LNG 3.12	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 12: Rigid fuel line in copper and its alloys	2022	CSA	Vehicle
CSA/ANSI LNG 3.13	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 13: Tank pressure control regulator	2022	CSA	Vehicle
CSA/ANSI LNG 3.14	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 14: Differential pressure fuel content gauge	2022	CSA	Vehicle
CSA/ANSI LNG 3.15	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 15: Capacitance fuel content gauge	2022	CSA	Vehicle
CSA/ANSI LNG 3.16	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 16: Heat exchanger–vaporizer	2022	CSA	Vehicle
CSA/ANSI LNG 3.18	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 18: Gas temperature sensor	2022	CSA	Vehicle
CSA/ANSI LNG 3.19	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 19: Automatic valve	2022	CSA	Vehicle
CSA/ANSI LNG 3.20	Road vehicles – Liquefied natural gas (LNG) fuel system components – Part 20: Flexible fuel or vent lines	2020	CSA	Vehicle
CSA/ANSI LNG 4.1	Liquified natural gas (LNG) dispensing systems for natural gas vehicles (NGV)	2018	CSA	Infrastructure
CSA/ANSI NGV 2	Compressed natural gas vehicle fuel containers	2019	CSA	Vehicle
CSA/ANSI NGV 4.1	Natural gas vehicle (NGV) dispensing systems	2018	CSA	Infrastructure
CSA/ANSI NGV 4.3	Temperature compensation for compressed natural gas vehicle fuelling	2022	CSA	Overarching
CSA/ANSI NGV 4.8	Natural gas vehicle fuelling station compressor packages	2021	CSA	Infrastructure
CSA/ANSI NGV 6.1	Compressed natural gas (CNG) fuel storage and delivery systems for road vehicles	2021	CSA	Vehicle
CSA/ANSI PRD 1	Pressure relief devices for natural gas vehicle (NGV) fuel containers	2020	CSA	Vehicle
CSA/IEC TS 61000-3-5	Electromagnetic compatibility (EMC) – Part 3-5: Limits – Limitation of voltage fluctuations and flicker in low-voltage power supply systems for equipment with rated current greater than 75 A	2021	CSA	Overarching

Designation	Title	Publication Year	Publisher	Topic
European Standards / Euronorm (EN)				
EN 17533	Gaseous hydrogen – Cylinders and tubes for stationary storage	2020	EN	Infrastructure
EN 45545	Fire Protection on Railway Vehicles	2013	EN	Vehicle
EN 50121-3-2	Railway applications – Electromagnetic compatibility – Part 3-2: Rolling stock – Apparatus	2019	EN	Vehicle
EN 50153	Railway applications – Rolling stock – Protective provisions relating to electrical hazards	2020	EN	Vehicle
EN 50343	Railway applications – Rolling stock – Rules for installation of cabling	2018	EN	Vehicle
International Electrotechnical Commission (IEC)				
IEC 60034-1	Rotating electrical machines – Part 1: Rating and performance	2017	IEC	Overarching
IEC 60079-10-1	Explosive atmospheres – Part 10-1: Classification of areas – Explosive gas atmospheres	2020	IEC	Overarching
IEC 60079-14	Explosive atmospheres – Part 14: Electrical installations design, selection and erection	2013	IEC	Overarching
IEC 60079-18	Explosive atmospheres – Part 18: Equipment protection by encapsulation "m"	2014	IEC	Overarching
IEC 60079-26	Explosive atmospheres – Part 26: Equipment with separation elements or combined levels of protection	2021	IEC	Overarching
IEC TS 60079-32-1	Explosive atmospheres – Part 32-1: Electrostatic hazards, guidance	2013	IEC	Overarching
IEC 60204-1	Safety of machinery – Electrical equipment of machines – Part 1: General requirements	2016	IEC	Overarching
IEC 60695-11-10	Fire hazard testing – Part 11-10: Test flames – 50 W horizontal and vertical flame test methods	2013	IEC	Overarching
IEC 60730-1	Automatic electrical controls – Part 1: General requirements	2013	IEC	Overarching
IEC 60730-2-6	Automatic electrical controls – Part 2-6: Particular requirements for automatic electrical pressure sensing controls including mechanical requirements	2015	IEC	Overarching
IEC 60730-2-9	Amendment 2 – Automatic electrical controls – Part 2-9: Particular requirements for temperature sensing control	2015	IEC	Overarching
IEC 60812	Failure modes and effects analysis (FMEA and FMECA)	2018	IEC	Overarching
IEC 61000-3-11	Electromagnetic compatibility (EMC) – Part 3-11: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems – Equipment with rated current ≤75 A and subject to conditional connection	2017	IEC	Overarching

Designation	Title	Publication Year	Publisher	Topic
IEC 61000-3-2	Electromagnetic compatibility (EMC) – Part 3-2: Limits – Limits for harmonic current emissions (equipment input current = 16 A per phase)	2018	IEC	Overarching
IEC 61000-3-3	Electromagnetic compatibility (EMC) – Part 3-3: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤16 A per phase and not subject to conditional connection	2013	IEC	Overarching
IEC TS 61000-3-4	Electromagnetic compatibility (EMC) – Part 3-4: Limits – Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A	1998	IEC	Overarching
IEC 61000-6-1	Electromagnetic compatibility (EMC) – Part 6-1: Generic standards - Immunity standard for residential, commercial and light-industrial environments	2016	IEC	Overarching
IEC 61000-6-2	Electromagnetic compatibility (EMC) – Part 6-2: Generic standards – Immunity standard for industrial environments	2016	IEC	Overarching
IEC 61000-6-4	Electromagnetic compatibility (EMC) – Part 6-4: Generic standards – Emission standard for industrial environments	2018	IEC	Overarching
IEC 61010-1	Safety Requirements for electrical equipment for measurement, control, and laboratory use – Part 1: General requirements	2010	IEC	Overarching
IEC 61010-2-202	Safety requirements for electrical equipment for measurement, control and laboratory use – Part 2-202: Particular requirements for electrically operated valve actuators	2020	IEC	Overarching
IEC 61025	Fault tree analysis (FTA)	2006	IEC	Overarching
IEC 61373	Railway applications – Rolling stock equipment – Shock and vibration tests	2010	IEC	Vehicle
IEC 61508-1	Functional safety of electrical/electronic/programmable electronic safety-related systems – Part 1: General requirements	2010	IEC	Overarching
IEC 61508-2	Functional safety of electrical/electronic/programmable electronic safety-related systems – Part 2: Requirements for electrical/electronic/programmable electronic/ safety-related systems	2010	IEC	Overarching
IEC 61508-3	Functional safety of electrical/electronic/programmable electronic safety-related systems – Part 3: Software requirements	2010	IEC	Overarching
IEC 61508-4	Functional safety of electrical/electronic/programmable electronic safety-related systems – Part 4: Definitions and abbreviations	2010	IEC	Overarching

Designation	Title	Publication Year	Publisher	Topic
IEC 61508-5	Functional safety of electrical/electronic/programmable electronic safety-related systems – Part 5: Examples of methods for the determination of safety integrity levels	2010	IEC	Overarching
IEC 61508-6	Functional safety of electrical/electronic/programmable electronic safety-related systems – Part 6: Guidelines on the application of IEC 61508-2 and IEC 61508-3	2010	IEC	Overarching
IEC 61508-7	Functional safety of electrical/electronic/programmable electronic safety-related systems – Part 7: Overview of techniques and measures	2010	IEC	Overarching
IEC 61810-1	Electromechanical Elementary Relays – Part 1: General Requirements	2015	IEC	Overarching
IEC 61851-1	Electric vehicle conductive charging system – Part 1: General requirements	2017	IEC	Infrastructure
IEC 61882	Hazard and operability studies (HAZOP studies) – Application guide	2016	IEC	Overarching
IEC 61980-1	Electric vehicle wireless power transfer (WPT) systems – Part 1: General requirements	2020	IEC	Infrastructure
IEC 61980-2	Electric vehicle wireless power transfer (WPT) systems – Part 2: Specific requirements for MF-WPT system communication and activities	2023	IEC	Infrastructure
IEC 61980-3	Electric vehicle wireless power transfer (WPT) systems – Part 3: Specific requirements for magnetic field wireless power transfer systems	2022	IEC	Infrastructure
IEC 62061	Safety of machinery: Functional safety of safety-related control systems	2005	IEC	Overarching
IEC 62196-1	Plugs, socket-outlets, vehicle connectors and vehicle inlets – Conductive charging of electric vehicles – Part 1: General requirements	2022	IEC	Vehicle
IEC 62282-4-101	Fuel cell technologies – Part 4-101: Fuel cell power systems for electrically powered industrial trucks – Safety	2022	IEC	Vehicle
IEC 62282-4-102	Fuel cell technologies – Part 4-102: Fuel cell power systems for industrial electrically powered industrial trucks – Performance test methods	2022	IEC	Vehicle
IEC 62282-5-100	Fuel cell technologies – Part 5-100: Portable fuel cell power systems – Safety	2018	IEC	Vehicle
IEC 62485-3	Safety requirements for secondary batteries and battery installations – Part 3: Traction batteries	2014	IEC	Vehicle
IEC 62619	Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries, for use in industrial applications	2022	IEC	Overarching
IEC 62620	Secondary cells and batteries containing alkaline or other non-acid electrolytes – Secondary lithium cells and batteries for use in industrial applications	2014	IEC	Overarching

Designation	Title	Publication Year	Publisher	Topic
IEC 62660-1	Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 1: Performance testing	2018	IEC	Vehicle
IEC 62660-3	Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 3: Safety requirements	2022	IEC	Vehicle
IEC 62864-1	Railway applications – Rolling stock – Power supply with onboard energy storage system – Part 1: Series hybrid system	2016	IEC	Vehicle
IEC 62928	Railway applications – Rolling stock – Onboard lithium-ion traction batteries	2017	IEC	Vehicle
IEC 63341-1	Railway applications – Rolling stock – Fuel cell systems for propulsion – Part 1: Fuel cell power system	Draft	IEC	Vehicle
IEC 63341-2	Railway applications – Rolling stock – Fuel cell systems for propulsion – Part 2: Hydrogen storage system	Draft	IEC	Vehicle
Institute of Electrical and Electronics Engineers (IEEE)				
IEEE 16	IEEE Standard for Electrical and Electronic Control Apparatus on Rail Vehicles	2020	IEEE	Vehicle
International Standards Organization (ISO)				
ISO 1182	Reaction to fire tests for products – Non-combustibility test	2020	ISO	Overarching
ISO 4126-1	Safety devices for protection against excessive pressure – Part 1: Safety valves	2013	ISO	Overarching
ISO 4126-5	Safety devices for protection against excessive pressure – Part 5: Controlled safety pressure relief systems (CSPRS)	2013	ISO	Overarching
ISO 4414	Pneumatic fluid power – General rules and safety requirements for systems and their components	2010	ISO	Overarching
ISO 6469-1	Electrically propelled road vehicles – Safety specifications – Part 1: Rechargeable energy storage system (RESS)	2019	ISO	Vehicle
ISO 6469-2	Electrically propelled road vehicles – Safety specifications – Part 2: Vehicle operational safety	2022	ISO	Vehicle
ISO 6469-3	Electrically propelled road vehicles – Safety specifications – Part 3: Electrical safety	2021	ISO	Vehicle
ISO 10439-1	Petroleum, petrochemical and natural gas industries – Axial and centrifugal compressors and expander-compressors – Part 1: General requirements	2015	ISO	Infrastructure
ISO 10439-2	Petroleum, petrochemical and natural gas industries - Axial and centrifugal compressors and expander-compressors – Part 2: Non-integrally geared centrifugal and axial compressors	2015	ISO	Infrastructure

Designation	Title	Publication Year	Publisher	Topic
ISO 10439-3	Petroleum, petrochemical and natural gas industries – Axial and centrifugal compressors and expander-compressors – Part 3: Integrally geared centrifugal compressors	2015	ISO	Infrastructure
ISO 10439-4	Petroleum, petrochemical and natural gas industries – Axial and centrifugal compressors and expander-compressors – Part 4: Expander-compressors	2015	ISO	Infrastructure
ISO 10440-1	Petroleum, petrochemical and natural gas industries – Rotary-type positive-displacement compressors – Part 1: Process compressors	2007	ISO	Infrastructure
ISO 10440-2	Petroleum and natural gas industries – Rotary-type positive-displacement compressors – Part 2: Packaged air compressors (oil-free)	2001	ISO	Infrastructure
ISO 10442	Petroleum, chemical and gas service industries – Packaged, integrally geared centrifugal air compressors	2002	ISO	Infrastructure
ISO 11114-1	Gas cylinders – Compatibility of cylinder and valve materials with gas contents – Part 1: Metallic materials	2020	ISO	Vehicle
ISO 11114-2	Gas cylinders – Compatibility of cylinder and valve materials with gas contents – Part 2: Non-metallic materials	2021	ISO	Vehicle
ISO 11114-3	Gas cylinders – Compatibility of cylinder and valve materials with gas contents – Part 3: Autogenous ignition test for non-metallic materials in oxygen atmosphere	2010	ISO	Vehicle
ISO 11114-4	Transportable gas cylinders – Compatibility of cylinder and valve materials with gas contents – Part 4: Test methods for selecting steels resistant to hydrogen embrittlement	2017	ISO	Overarching
ISO 11363-1	Gas cylinders – 17E and 25E taper threads for connection of valves to gas cylinders – Part 1: Specifications	2018	ISO	Overarching
ISO 11363-2	Gas cylinders – 17E and 25E taper threads for connection of valves to gas cylinders – Part 2: Inspection gauges	2017	ISO	Overarching
ISO 11439	Gas cylinders – High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles + Amendment 1 (published in 2021)	2013	ISO	Vehicle
ISO 12100	Safety of machinery – General principles for design – Risk assessment and risk reduction	2010	ISO	Overarching
ISO 12405-4	Electrically propelled road vehicles – Test specification for lithium-ion traction battery packs and systems – Part 4: Performance testing	2018	ISO	Vehicle
ISO 13631	Petroleum and natural gas industries – Packaged reciprocating gas compressors	2002	ISO	Infrastructure
ISO 13707	Petroleum and natural gas industries – Reciprocating compressors	2000	ISO	Infrastructure

Designation	Title	Publication Year	Publisher	Topic
ISO 13849-1	Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design	2023	ISO	Overarching
ISO 13849-2	Safety of machinery – Safety-related parts of control systems – Part 2: Validation	2012	ISO	Overarching
ISO 13850	Safety of machinery – Emergency stop function – Principles for design	2015	ISO	Overarching
ISO 13984	Liquid hydrogen – Land vehicle fuelling system interface	1999	ISO	Infrastructure
ISO 13985	Liquid hydrogen – Land vehicle fuel tanks	2006	ISO	Vehicle
ISO 14687	Hydrogen fuel – Product specification	2019	ISO	Overarching
ISO TR-15916	Basic considerations for the safety of hydrogen systems	2015	ISO	Overarching
ISO 16110-1	Hydrogen generators using fuel processing technologies – Part 1: Safety	2007	ISO	Infrastructure
ISO 16110-2	Hydrogen generators using fuel processing technologies – Part 2: Test methods for performance	2010	ISO	Infrastructure
ISO 16111	Transportable gas storage devices – Hydrogen absorbed in reversible metal hydride	2018	ISO	Vehicle
ISO 16528-1	Boilers and pressure vessels – Part 1: Performance requirements	2007	ISO	Overarching
ISO 17268	Gaseous hydrogen land vehicle refuelling connection devices	2020	ISO	Infrastructure
ISO 19078	Gas cylinders – Inspection of the cylinder installation, and requalification of high pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles	2013	ISO	Vehicle
ISO 19880-1	Gaseous hydrogen – Fuelling stations – Part 1: General requirements	2020	ISO	Infrastructure
ISO 19880-3	Gaseous hydrogen – Fuelling stations – Part 3: Valves	2018	ISO	Infrastructure
ISO 19880-5	Gaseous hydrogen – Fuelling stations – Part 5: Dispenser hoses and hose assemblies	2019	ISO	Infrastructure
ISO 19880-8	Gaseous hydrogen – Fuelling stations – Part 8: Fuel quality control + Amendment 1 (published in 2021)	2019	ISO	Infrastructure
ISO 19881	Gaseous hydrogen – Land vehicle fuel containers	2018	ISO	Vehicle
ISO 19882	Gaseous hydrogen – Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers	2018	ISO	Vehicle
ISO 19887	Gaseous hydrogen – Fuel system components for hydrogen fuelled vehicles	Under development	ISO	Vehicle

Designation	Title	Publication Year	Publisher	Topic
ISO 21010	Cryogenic vessels – Gas/materials compatibility	2017	ISO	Overarching
ISO 21014	Cryogenic vessels – Cryogenic insulation performance	2019	ISO	Overarching
ISO 21028-1	Cryogenic vessels – Toughness requirements for materials at cryogenic temperature – Part 1: Temperatures below -80 degrees C	2016	ISO	Overarching
ISO 21087	Gas analysis – Analytical methods for hydrogen fuel – Proton exchange membrane (PEM) fuel cell applications for road vehicles	2019	ISO	Overarching
ISO 23208	Cryogenic vessels – Cleanliness for cryogenic service	2017	ISO	Overarching
ISO 23273-1	Fuel cell road vehicles – Safety specifications – Part 1: Vehicle functional safety	2013	ISO	Vehicle
ISO 23273-2	Fuel cell road vehicles – Safety specifications – Part 2: Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen	2013	ISO	Vehicle
ISO 24490	Cryogenic vessels – Pumps for cryogenic service	2016	ISO	Infrastructure
ISO 26142	Hydrogen detection apparatus – Stationary applications	2010	ISO	Infrastructure
Japanese Standards Association (JSA)				
JSA JIS H 7003	Glossary of terms used in hydrogen absorbing alloys	2021	JSA	Overarching
JSA JIS H 7201	Method for measurement of pressure-composition-temperature (PCT) relations of hydrogen absorbing alloys	2011	JSA	Overarching
JSA JIS H 7202	Method for measurement of hydrogen absorption/desorption reaction rate of hydrogen absorbing alloys	2022	JSA	Overarching
JSA JIS H 7203	Method for measurement of hydrogen absorption/desorption cycle characteristic of hydrogen absorbing alloys	2021	JSA	Overarching
National Association of Corrosion Engineers (NACE)				
ANSI/NACE TM0284	Evaluation of pipeline and pressure vessel steels for resistance to hydrogen-induced cracking	2016	NACE	Overarching
National Fire Protection Association (NFPA)				
NFPA 2	Hydrogen Technologies Code	2023	NFPA	Overarching
NFPA 52	Vehicular Natural Gas Fuel Systems Code	2023	NFPA	Overarching
NFPA 55	Compressed Gases and Cryogenic Fluids Code	2023	NFPA	Overarching
NFPA 68	Standard on Explosion Protection by Deflagration Venting	2023	NFPA	Overarching
NFPA 69	Standard on Explosion Prevention Systems	2019	NFPA	Overarching

Designation	Title	Publication Year	Publisher	Topic
NFPA 70	National Electrical Code	2005	NFPA	Overarching
NFPA 77	Recommended Practice on Static Electricity	2024	NFPA	Overarching
NFPA 80A	Recommended Practice for Protection of Buildings from Exterior Fire Exposures	2022	NFPA	Infrastructure
NFPA 91	Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Particulate Solids	2020	NFPA	Overarching
NFPA 130	Standard for Fixed Guideway Transit and Passenger Rail Systems	2023	NFPA	Overarching
NFPA 274	Standard Test Method to Evaluate Fire Performance Characteristics of Pipe Insulation	2023	NFPA	Overarching
NFPA 329	Recommended Practice for Handling Releases of Flammable and Combustible Liquids and Gases	2020	NFPA	Overarching
NFPA 400	Hazardous Materials Code	2022	NFPA	Overarching
NFPA 496	Standard for Purged and Pressurized Enclosures for Electrical Equipment	2024	NFPA	Vehicle
NFPA 497	Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas	2024	NFPA	Overarching
NFPA 551	Guide for the Evaluation of Fire Risk Assessments	2022	NFPA	Overarching
NFPA 853	Standard for the Installation of Stationary Fuel Cell Power Systems	2020	NFPA	Infrastructure
NFPA 855	Standard for the Installation of Stationary Energy Storage Systems	2023	NFPA	Infrastructure
Rail Industry Safety and Standards Board (RISSB)				
RISSB AS 7486	Railway energy storage: Rolling stock onboard electrical energy storage	2022	RISSB	Vehicle
Society of Automotive Engineers (SAE)				
SAE J1616	Recommended Practice for Compressed Natural Gas Vehicle Fuel	2017	SAE	Overarching
SAE J1739	Potential Failure Mode and Effects Analysis (FMEA) Including Design FMEA, Supplemental FMEA-MSR, and Process FMEA	2021	SAE	Overarching
SAE J1766	Recommended Practice for Electric, Fuel Cell and Hybrid Electric Vehicle Crash Integrity Testing	2014	SAE	Vehicle
SAE J1772	SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler	2017	SAE	Vehicle
SAE J1798	Recommended Practice for Performance Rating of Electric Vehicle Battery Modules	2019	SAE	Vehicle

Designation	Title	Publication Year	Publisher	Topic
SAE J2344	Guidelines for Electric Vehicle Safety	2010	SAE	Vehicle
SAE J2380	Vibration Testing of Electric Vehicle Batteries	2021	SAE	Vehicle
SAE J2464	Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing	2021	SAE	Vehicle
SAE J2578	Recommended Practice for General Fuel Cell Vehicle Safety	2014	SAE	Vehicle
SAE J2579	Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles	2018	SAE	Vehicle
SAE J2594	Recommended Practice to Design for Recycling Proton Exchange Membrane (PEM) Fuel Cell Systems	2023	SAE	Vehicle
SAE J2600	Compressed Hydrogen Surface Vehicle Fueling Connection Devices	2015	SAE	Infrastructure
SAE J2601	Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles	2020	SAE	Vehicle
SAE J2615	Testing Performance of Fuel Cell Systems for Automotive Applications	2011	SAE	Vehicle
SAE J2616	Testing Performance of the Fuel Processor Subsystem of an Automotive Fuel Cell System	2011	SAE	Vehicle
SAE J2617	Recommended Practice for Testing Performance of PEM Fuel Cell Stack Sub-System for Automotive Applications	2011	SAE	Vehicle
SAE J2719	Hydrogen Fuel Quality for Fuel Cell Vehicles	2020	SAE	Vehicle
SAE J2799	Hydrogen Surface Vehicle to Station Communications Hardware and Software	2019	SAE	Infrastructure
SAE J2929	Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems	2013	SAE	Vehicle
SAE J2990	Hybrid and EV First and Second Responder Recommended Practice	2019	SAE	Vehicle
SAE J2990/1	Gaseous Hydrogen and Fuel Cell Vehicle First and Second Responder Recommended Practice	2016	SAE	Vehicle
SAE J3071	Automotive Battery Recycling Identification and Cross Contamination Prevention	2016	SAE	Vehicle
SAE J3121	Hydrogen Vehicle Crash Test Lab Safety Guidelines	2022	SAE	Vehicle
SAE J3219	Hydrogen Fuel Quality Screening Test of Chemicals for Fuel Cell Vehicles	2022	SAE	Vehicle
SAE J3271 (WIP)	Megawatt Charging System for Electric Vehicles	TBD	SAE	Infrastructure
Swiss Standards Association (SNV)				
SNV SNG 10000	Guide to setting up hydrogen fuelling stations	2019	SNV	Infrastructure

Designation	Title	Publication Year	Publisher	Topic
Standards Press of China (SPC)				
SPC GB/T 26466	Stationary flat steel ribbon wound vessels for storage of high-pressure hydrogen	2011	SPC	Infrastructure
SPC GB/T 33291	Measurement method of pressure-composition-temperature for reversible hydrogen absorption and desorption of hydrides	2016	SPC	Overarching
SPC GB/T 33292	Metal hydride hydrogen storage system for fuel cells backup power	2016	SPC	Infrastructure
SPC GB/T 34542.1	Storage and transportation systems for gaseous hydrogen – Part 1: General requirements	2017	SPC	Infrastructure
SPC GB/T 34583	Safety technical requirements for hydrogen storage devices used in hydrogen fuelling station	2017	SPC	Infrastructure
Underwriters Laboratories (UL)				
UL 1203	Standard for Explosion-Proof and Dust-Ignition-Proof Electrical Equipment for Use in Hazardous (Classified) Locations	2023	UL	Overarching
UL 1642	Lithium Batteries	2022	UL	Overarching
ANSI/CAN/UL 1973	Batteries for Use in Stationary and Motive Auxiliary Power Applications	2022	UL	Overarching
ANSI/CANUL 1974	Standard for Evaluation for Repurposing Batteries	2018	UL	Overarching
UL 1998	Standard for Software in Programmable Components	2022	UL	Overarching
UL 2017	Standard for General-Purpose Signaling Devices and Systems	2008	UL	Overarching
UL 2075	Standard for Gas and Vapor Detectors and Sensors	2023	UL	Overarching
UL 2249	Outline of Investigation for Hydrogen Fuel Dispensing Systems	2020	UL	Infrastructure
UL 2262	Outline of Investigation for Fuel Cell Modules for Use in Portable and Stationary Equipment	2012	UL	Overarching
UL 2264	Subject 2264 Gaseous Hydrogen Generation Appliances	2021	UL	Infrastructure
UL 2264A	Outline of Investigation for Water Electrolysis Type Hydrogen Generators	2021	UL	Infrastructure
UL 2267	Standard for Fuel Cell Power Systems for Installation in Industrial Electric Trucks	2020	UL	Vehicle
UL 2271	ANSI/CAN/UL/ULC Standard for Batteries for Use In Light Electric Vehicle (LEV) Applications	2018	UL	Vehicle
UL 2580	Batteries for Use In Electric Vehicles	2022	UL	Vehicle
UL 2591	Outline of Investigation for Battery Cell Separators	2018	UL	Overarching

Designation	Title	Publication Year	Publisher	Topic
UL 2596	Test Method for Thermal and Mechanical Performance of Battery Enclosure Materials	2022	UL	Overarching
UL 268	Standard for Smoke Detectors for Fire Alarm Systems	2023	UL	Overarching
UL 2734	Connectors and Service Plugs for Use with On-Board Electrical Vehicle (EV) Charging Systems	2020	UL	Vehicle
UL 4128	Outline of Investigation for Intercell and Intertier Connectors for Use in Electrochemical Battery System Applications	2020	UL	Overarching
UL 429	Standard for Electrically Operated Valves	2013	UL	Overarching
UL 458	Standard for Power Converters/Inverters and Power Converter/Inverter Systems for Land Vehicles and Marine Crafts	2015	UL	Vehicle
UL 5800	ANSI/CAN/UL Battery Fire Containment Products	2020	UL	Overarching
UL 583	Electric-Battery-Powered Industrial Trucks	2022	UL	Vehicle
UL 60079-17	Explosive Atmospheres – Part 17: Electrical Installations Inspection and Maintenance	2017	UL	Overarching
UL 60335-2-34	Household and Similar Electrical Appliances – Safety – Part 2-34: Particular Requirements for Motor-Compressors	2017	UL	Infrastructure
UL 62133	Standard For Safety For Secondary Cells And Batteries Containing Alkaline Or Other Non-Acid Electrolytes – Safety Requirements For Portable Sealed Secondary Cells, And For Batteries Made From Them, For Use In Portable Applications	2017	UL	Vehicle
UL 62133-1	Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes – Safety Requirements for Portable Sealed Secondary Cells, and for Batteries Made from Them, for Use in Portable Applications – Part 1: Nickel Systems	2020	UL	Vehicle
UL 62133-2	Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes – Safety Requirements for Portable Sealed Secondary Cells, and for Batteries Made from Them, for Use in Portable Applications – Part 2: Lithium Systems	2020	UL	Vehicle
UL 746C	Standard for Polymeric Materials – Use in Electrical Equipment Evaluations	2023	UL	Overarching
UL 80079-36	Explosive Atmospheres – Part 36: Non-Electrical Equipment for Explosive Atmospheres – Basic Method and Requirements	2021	UL	Overarching
UL 80079-37	Explosive Atmospheres – Part 37: Non-Electrical Equipment for Explosive Atmospheres – Non Electrical Type of Protection Constructional Safety	2021	UL	Overarching
UL 864	Standard for Control Units and Accessories for Fire Alarm Systems	2014	UL	Overarching
UL 913	Intrinsically Safe Apparatus and Associated Apparatus for Use in Class I, II, and III, Division 1, Hazardous (Classified) Locations	2013	UL	Overarching

Designation	Title	Publication Year	Publisher	Topic
UL 94	Standard for Tests for Flammability of Plastic Materials for Parts in Devices and Appliances	2023	UL	Overarching
UL 9540A	ANSI/CAN/UL Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems	2019	UL	Overarching
UL 991	Standard for Tests for Safety-Related Controls Employing Solid-State Devices	2010	UL	Overarching

Table B-2: Applicable Codes and Regulations

Designation	Title	Publication Year	Publisher	Topic
Government of Canada (Gov. Can.) / Transport Canada (TC)				
R.S.C., 1985, c. L-2	Canada Labour Code	2023	Gov. Can.	Overarching
SOR/87-184	On Board Trains Occupational Safety and Health Regulations	2023	Gov. Can.	Vehicle
SOR/2015-26	Railway Safety Management System Regulations	2015	Gov. Can.	Overarching
SOR/87-150	Railway Employee Qualification Standards Regulations	2023	Gov. Can.	Overarching
SOR/2001-286	Transportation of Dangerous Goods Regulations	2023	TC	Overarching
United States Department of Transportation (US DOT)				
49 CFR Part 172	Hazardous Materials Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, Training Requirements, And Security Plans	2023	US DOT	Vehicle
49 CFR Part 173	Shippers – General Requirements for Shipments and Packagings	2023	US DOT	Overarching
49 CFR Part 179	Federal Railroad Administration – Code of federal regulations, Title 49 – Transportation, Part 179 – Specifications for Tank Cars	2023	US DOT	Vehicle
49 CFR Part 213	Federal Railroad Administration – Code of federal regulations, Title 49 – Transportation, Part 213 – Track Safety Standards	2023	US DOT	Infrastructure
49 CFR Part 223	Federal Railroad Administration – Code of federal regulations, Title 49 – Transportation, Part 223 – Safety Glazing Standards – Locomotives, Passenger Cars and Cabooses	2023	US DOT	Vehicle
49 CFR Part 227	Federal Railroad Administration – Code of federal regulations, Title 49 – Transportation, Part 227 – Occupational Noise Exposure	2023	US DOT	Vehicle
49 CFR Part 229	Federal Railroad Administration – Code of federal regulations, Title 49 – Transportation, Part 229 – Railroad Locomotive Safety Standards	2023	US DOT	Vehicle
49 CFR Part 238	Federal Railroad Administration – Code of federal regulations, Title 49 – Transportation, Part 238 – Passenger Equipment Safety Standards	2023	US DOT	Vehicle

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

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