

STANDARDS RESEARCH

Canada's Railway Electrification Ecosystem: A Standardization Roadmap

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List of Abbreviations

AC	Alternating current
AEUC	Alberta Electrical Utility Code
APTA	American Public Transportation Association
AREMA	American Railway Engineering and Maintenance-of-Way Association
ASTM	American Society for Testing and Materials
CEC	Canadian Electrical Code
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
DC	Direct Current
FRA	Federal Railroad Administration
GHG	Greenhouse Gas
HSR	High Speed Rail
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
LRT	Light Rail Transit
NFPA	National Fire Protection Association
OCS	Overhead Catenary Systems
RAMS	Reliability, Availability, Maintainability and Safety
TPSS	Traction Power Substations
UIC	International Union of Railways
VTS/TPSSC	Vehicular Technology Society Traction Power Systems Standards Committee

Executive Summary

Railway electrification and decarbonization projects are gaining momentum in Canada and across North America, which can strengthen local and regional transport networks. Railways can also play a crucial role in reducing greenhouse gas (GHG) emissions and helping Canada achieve sustainable transportation goals. However, the absence of a harmonized standard for railway electrification in North America and the current patchwork of systems and practices being used across jurisdictions complicates interoperability and project development.

This research report describes the current standards landscape affecting railway electrification projects in Canada, with a focus on stationary electrical traction power infrastructure located behind the meter and upstream of rolling stock, including traction power substations (TPSS), power transmission and distribution, grounding and bonding, and overhead catenary systems (OCS).

The research included a comprehensive literature review of existing standards, regulations, and international electrification initiatives, followed by a gap analysis to identify challenges and best practices for the design, implementation, maintenance, and operation of electrified railways. Industry experts were also engaged through a survey and a series of interviews to inform and validate the analysis. Findings were used to identify systemic issues and standardization gaps across multiple technical and organizational domains, and to develop evidence-based recommendations to facilitate railway electrification in Canada.

The findings indicate that current standards do not fully address Canadian operating conditions. Standardization gaps were identified in the design, maintenance, and inspection of traction power infrastructure. In specific applications, such as high-speed rail (HSR) or electric freight rail, existing standards lack the depth and scope to support current projects. Gaps were also noted in standardized recognition of the workforce skills and training pathways for professionals involved in traction power component installation.

Overall, the absence of harmonized standards contributes to inconsistent practices across the industry with limited knowledge transfer between projects, and an over-reliance on individual expertise. There is a need for nationally relevant guidance that complements international standards, and for standards that reflect Canada's unique climatic conditions, diversity of rail systems, jurisdictional complexity, and diverse models of project development.

The recommendations presented in this report support the effective rollout of railway electrification projects in Canada by tackling current challenges reported by the industry, facilitating implementation of systems, supporting interoperability, and encouraging innovation, without imposing undue burdens on suppliers or excluding proven solutions from the global market. Broadly, the recommendations address the following key goals:

- Build on international standards for the Canadian context;
- Develop national application guidelines for existing standards;
- Develop Canadian standards for dedicated systems or applications, including traction power, HSR, and freight rail;

- Develop a Canadian standard on reliability, availability, maintainability and safety (RAMS) studies for railway electrification;
- Develop a standardized framework for project presentation, with consistent cost categories, formatting conventions, and key performance indicators;
- Establish a nationally standardized inspection framework for railway power installations;
- Develop new or expand on current standards for the maintenance of both AC and DC traction power systems, and for work safety practices for traction power systems; and
- Develop nationally standardized training and certification programs for the electrified railway field.

By addressing inefficiencies across all phases of railway electrification projects, these recommendations could promote cost-effective engineering, minimize overdesign, and empower rail operators and transit agencies to better define and implement their operational and lifecycle requirements. Ultimately, these efforts could help establish a more coherent, resilient, and future-ready rail electrification ecosystem in Canada.



"In 2021, transportation accounted for approximately 25% of Canada's national greenhouse gas (GHG) emissions, with railways representing just 4.7% of transportation emissions, making them the most GHG-efficient land transport mode per kilometre travelled."

1. Background and Objectives

Electricity has played a crucial role in the evolution of Canada's rail systems, with Windsor, Ontario becoming the first city to install electric tram systems in 1886 [1]. By the 1920s, 48 Canadian cities had streetcar networks connecting urban neighbourhoods, but these systems have declined since the 1930s due to competition from automobiles, motorbuses, and trolleybuses [1].

In heavy rail networks, early propulsion was powered by coal-fired steam engines [2]. The 1950s marked a shift toward diesel-electric locomotives, which offer higher energy efficiency, better performance, and lower operational costs [2], [3], [4]. Using electric motors for propulsion, diesel-electric systems generate electricity onboard using diesel, while electric locomotives draw power directly from overhead lines or onboard batteries [2]. Notable early uses of fully electric traction include the 1915 Mont Royal tunnel in Montreal [2] and BC Rail's Tumbler Ridge Subdivision, a freight train that operated on electric traction for 15 years to avoid tunnel ventilation costs [5].

Canada's railway infrastructure is a vital component of its national transportation system. The freight network spans over 40,000 km, with two major rail companies handling approximately 70% of all intercity freight [6]. While the intercity passenger network is smaller (17,166 km), according to the Railway Association of Canada, the services were used by a total of 101.9 million commuters and 5.3 million intercity rail passengers in 2019 [3].

Commuter rail systems operate in Montreal, Toronto, and Vancouver, and predominantly use diesel-electric locomotives [3]. Urban electric rail systems also persist, including subways and modern light rail transit (LRT) systems, such as Edmonton's LRT and Vancouver's SkyTrain, which offer greater capacity and operational efficiency than early 20th-century streetcars [1].

In 2021, transportation accounted for approximately 25% of Canada's national greenhouse gas (GHG) emissions, with railways representing just 4.7% of transportation emissions, making them the most GHG-efficient land transport mode per kilometre travelled [7], [8], [9]. Recent developments, including high-speed rail (HSR) systems [10], [11], commuter train electrification efforts [12], and new LRT and tramway projects [13], [14], increasingly rely on electric propulsion systems, which enable the use of renewable energy sources and further reduce GHG emissions. However, these projects face persistent barriers to implementation, including political discontinuity [15], funding constraints [16], and other technical and regulatory challenges [15], [17], [18].

Railways can play a crucial role in reducing carbon emissions and achieving sustainable transportation goals, but challenges exist [19], [20], [21], and the absence of a harmonized standard for railway electrification in North America is one of the most cited challenges [22]. The current patchwork of systems across jurisdictions further complicates interoperability and project development. This

research report identifies standardization gaps and presents evidence-based recommendations to facilitate railway electrification in Canada.

1.1 Research Objectives

The main objectives of this research were to:

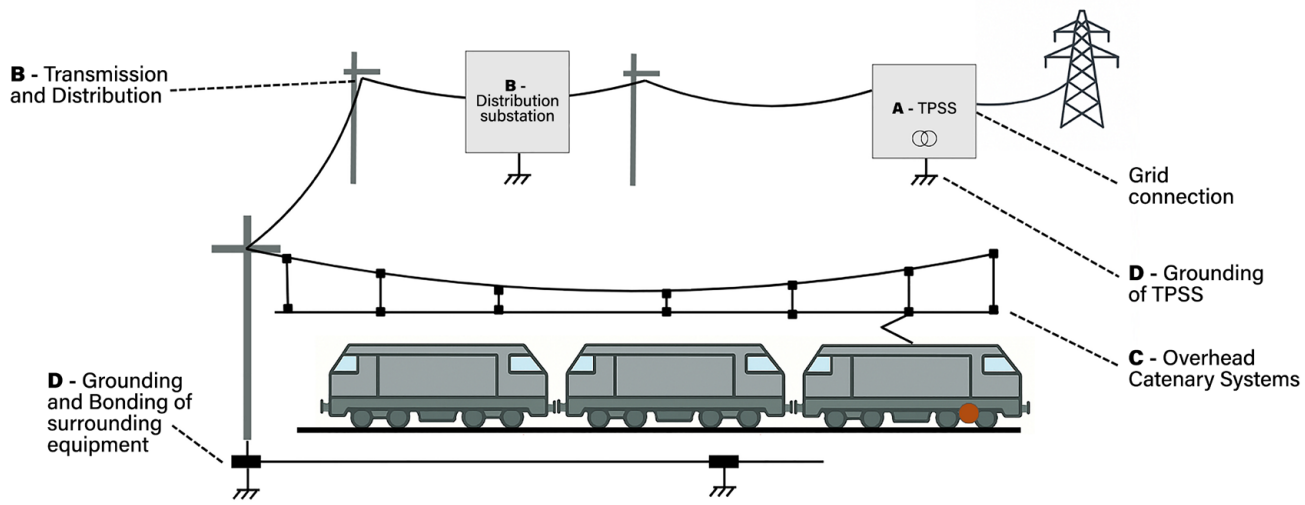
- Review the current standardization landscape for electrified railway systems in North America, including freight, high-speed passenger, and LRT, with a focus on Canada;
- Evaluate international electrification best practices to assess their applicability and transferability to the Canadian context;
- Identify ongoing federal, provincial, and territorial initiatives related to railway electrification, including their regulatory frameworks; and
- Identify gaps in the current Canadian standardization landscape and provide evidence-based recommendations, including requirements for standards, policy, training, and research to support railway electrification deployment in Canada.

1.2 Scope and Technical Focus

This report focuses on fully electric rail systems powered by the utility power grid. It examines traction power components and infrastructure located between the utility's connection point (i.e., the metre) and the rolling stock, the portion commonly referred to as "behind the metre." These systems are essential for delivering reliable and efficient traction power to locomotives or equivalent driving rail vehicles. The main components of traction power in rail electrification systems, shown in Figure 1, can be categorized into four key sub-elements:

- **A—Traction Power Substations (TPSS):** These substations convert high voltage AC power from the utility grid to the appropriate voltage and current type (AC or DC) required for railway operations. In DC systems, transformer rectifier units are used, which combine centrally tapped transformers and rectifier units to step down the voltage and generate DC power supply for onboard electric trains [23].
- **B—Power Transmission and Distribution:** This encompasses the infrastructure needed to deliver electricity from the traction power substations to the

Figure 1: Typical arrangement of rail electrification power systems.



overhead system and third rail system, and includes power lines, switchgear, load break switches, negative switchboards, and related equipment that ensure efficient power delivery to the rail system [23], [24].

- **C—Overhead Catenary Systems (OCS):** Overhead catenary wires are suspended above railway tracks to supply electricity to trains via pantographs. This system maintains continuous electrical contact and efficient energy transfer, while allowing return current to flow back to the TPSS [23].
- **D—Grounding and Bonding:** Critical for safety, grounding (or earthing) and bonding systems ensure proper path of the traction current via grounding of the support infrastructure and the different energized components (e.g., OCS, TPSS) as well as the management of return current to power stations [23].

1.3 Application Types

The types of rail applications considered in this report are listed in Table 1. Including these rail applications within the scope of the report allows for a thorough evaluation of the technical and regulatory contexts.

2 Methods

The research conducted for this report used a multi-faceted approach to assess the standardization landscape of railway electrification in Canada. It began with a comprehensive literature review to evaluate existing standards, regulations, and international electrification initiatives. This was followed by a targeted analysis of select rail projects to examine how current standards are being applied in practice and to identify recurring challenges or best practices for the design, implementation, maintenance, and operation of electrified railways. Finally, industry was engaged through a survey and a series of interviews with relevant interested parties. The findings were used to identify gaps and opportunities for the development or adaptation of rail electrification standards in the Canadian context. The gaps and opportunities reflect recurring technical, regulatory, and operational challenges that may hinder the effective deployment of railway electrification projects, and they inform the recommendations provided in this report.

2.1 Literature Review and Gap Analysis

A comprehensive literature review of current rail electrification initiatives and publications was conducted to identify recent projects, standards, and policies that support rail electrification in Canada, the United States (US), and internationally. This detailed analysis of academic and grey literature included technical publications and guidance documents from the following key standards development and industry organizations:

- American Public Transportation Association (APTA): US and Canada
- American Railway Engineering and Maintenance-of-Way Association (AREMA): North America
- European Committee for Standardization (CEN): Europe
- European Committee for Electrotechnical Standardization (CENELEC): Europe
- Canadian Standards Association (CSA Group): Canada

Table 1: Types of Rail Applications Evaluated

Rail Application	Description
High-Speed Rail (HSR)	Defined as rail systems capable of operating at speeds at or above 200 km/h, as defined by the International Union of Railways (UIC) [25].
Freight and Passenger Rail	Including regional, intercity, commuter, and suburban rail systems operating below 200 km/h.
Urban Rail Systems	Including light rail, streetcar, tramway, metro, and subway systems.

- International Electrotechnical Commission (IEC): International
- Institute of Electrical and Electronics Engineers Standards Association (IEEE SA): International
- National Fire Protection Association (NFPA): North America
- International Union of Railways (UIC): International

Standards, guidelines or codes were selected as relevant if they met one of the following criteria:

- The document's scope of application included at least one of the four sub-elements of traction power systems (OCS, TPSS, power transmission and distribution, or grounding and bonding); or
- The document addressed at least one key aspect of a rail project (initial study phase, design/conception, procurement of equipment, operations, or inspection or maintenance).

A subsequent gap analysis was conducted to identify inconsistencies and shortcomings within the current framework of codes and standards. The findings from the literature review and gap analysis highlighted areas where existing standards may be insufficient or outdated, which formed the basis for industry engagement in the form of a survey and interviews with relevant interested parties.

2.2 Industry Engagement

To deepen understanding of the processes and challenges faced by industry, the literature review was complemented by interviews with key subject matter experts involved in railway electrification projects. This approach captured a broad spectrum of perspectives from across the ecosystem of organizations that influence, implement, or are impacted by rail infrastructure development. Table 2 provides a list of the different types of groups that were engaged for participation in the survey and interviews.

Engagement consisted of an online survey followed by semi-structured interviews. Once a relevant contact was identified within an organization, the survey was distributed for initial input (see Appendix B.1). Respondents were then invited to participate in follow-up interviews to answer key questions on their experience with electrification projects and applicable standards (see Appendix B.2) and to further elaborate on their survey responses. Participant selection was

Table 2: Industry Groups Engaged for Survey and Interview Participation

Organization Type	Expected Perspectives and Insights
Associations and Consortia	Positions on the railway electrification landscape, perceived barriers, and views on standardization, depending on sector represented.
Energy Suppliers	Insights on the interface between railway electrification and utility infrastructure, including system impacts and coordination challenges.
Rail Companies	Current barriers to railway electrification and existing opportunities for standardization.
Rail Industry Suppliers and Rolling Stock Manufacturers	Lessons learned from project implementation and technical challenges related to existing codes and standards.
Transit Agencies	Perspectives on system planning, project delivery, and standardization needs based on practical experience.
Engineering Firms	Insights into the interpretation and application of standards in project design and procurement, and challenges faced during implementation.

based on current role and professional experience within the rail sector, ensuring a depth of knowledge across technical, regulatory, and operational domains.

This engagement phase provided valuable insights that complemented the literature review, including additional references to standards, project examples, and expert commentary on implementation practices. Figure 2 shows the breakdown of the 16 respondents that provided answers to the online survey by organization type. In total, 14 follow-up interviews were conducted.

Finally, a draft of the research findings was shared with the Project Advisory Panel for review and feedback. This iterative process helped to validate the report's conclusions and to ensure its relevance and applicability. The final report presents a detailed analysis of the current state of railway electrification codes and standards in Canada, identifying critical gaps and providing evidence-based recommendations for future standardization efforts.

3 Results

3.1 National and International Rail Electrification Initiatives

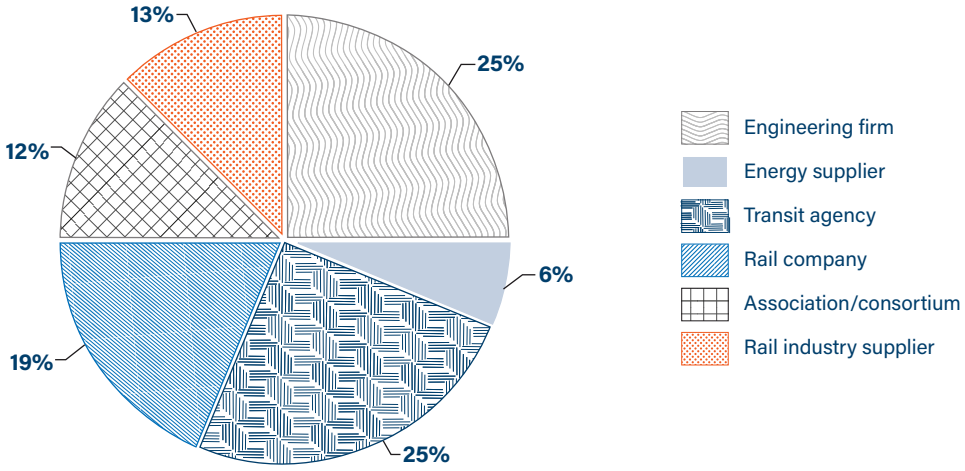
Across North America, there has been an increase in railway development and decarbonization initiatives, with Canada [22], the US [26], and Mexico [27] all announcing different railway development plans [28].

In Mexico, the government has published a national strategy for railway development and committed to building up to 3,000 km of railways. The plan includes several traction technologies, such as OCS systems and diesel-electric locomotives [29].

In the US, California has several initiatives underway, including the Caltrain electrification program [30], an HSR project, and state regulation on transport-related GHG emissions. In 2023, the California Air Resources Board passed a rule to accelerate the adoption of zero-emission propulsion technology in railways before withdrawing it in 2025 [31]. While hydrogen propulsion (hydrail) is not fully electric, industry interest in hydrail has grown in recent years, with initiatives to demonstrate its potential to decarbonize traction power implemented in Quebec [32] and in California [33].

In Canada, several electric railway initiatives are ongoing. At the national level, the federal government is advancing structural projects to push forward interprovincial rail, including the HSR corridor between Quebec City and Toronto [34]. Other federal initiatives include Transport Canada's 2023–2030 memorandum of understanding with the Railway Association of Canada to collaborate on rail decarbonization, which includes the following goal: "Advance decarbonization research and development, including government–industry cooperation on technology trials" [35]. In its 2023 overview report, Transport Canada also highlighted its collaboration with

Figure 2: Percentage of survey participants (n = 16) by type of organization.



the US Departments of Energy and Transportation via the creation of a Rail Decarbonization Task Force [7].

At the provincial level, the government of Alberta is developing a Passenger Rail Master Plan, which will include a 15-year delivery plan, for passenger rail services that are connected to municipal-led mass transit systems [36].

At the regional and municipal levels, there are many light and commuter rail projects in the conception or construction phase, including:

- Montreal's Réseau express métropolitain (REM) project, which has been partially commissioned [37];
- In southern Ontario, Metrolinx's GO Expansion program is electrifying its commuter train network [38];
- Vancouver is extending the Skytrain network both toward the west [39] and toward the east [40];
- Hamilton is progressing with the construction of its LRT system [41]; and
- Quebec City is developing a tramway line [42].

Electrified railway projects are not developed uniformly. Their characteristics (e.g., traction power, voltage levels, current type or system architecture) vary based on application, context, and location. Table 3 highlights projects around the world with their associated traction power systems, further illustrating the diversity in electrification system design. This variability highlights the importance of developing a uniform standard to ensure interoperability, reduce complexity, and enable scalability across regions and use cases.

Table 3: Examples of Rail Electrification Projects Around the World

Type	System Name	Location	Traction Power Characteristics	Launching	System Length
LRT	Ontario Line	Toronto, ON	1,500 V DC, OCS	2031 (est.)	15.6 km
	Skytrain	Vancouver Metropolitan Area, BC	650 V DC, 3rd rail 750 V DC, 3rd rail	1985 2009	79.6 km
	ION	Waterloo, ON	750 V DC, OCS	2019	19 km
	New Taipei Metro	Taiwan	750 V DC, OCS and 3rd rail	2018	9.55 km
	Toronto Streetcar System	Toronto, ON	600 V DC, OCS 750 V DC, OCS for newer lines	1892	83 km
	Calgary CTrain	Calgary, AB	600 V DC, OCS	1981	59.9 km
	REM	Montreal, QC	1,500 V DC, OCS	2023	16.6 km
	Sistema de Tren Eléctrico Urbano (lines 1 and 2)	Mexico	750 V DC, OCS	1989	46.5 km (total)
	Angers Tramway	France	750 V DC, OCS, and ground power	2010	22.4 km
Regional	IR Ishikawa Railway	Japan	20 kV AC, 60 Hz, OCS	1898	17.8 km
	El Insurgente	Mexico	25 kV AC, 60 Hz, OCS	2023	58 km
	South Shore Line	Chicago, US	1,500 V DC, OCS	1903	140 km
Freight	Deseret Power Railway	Utah, US	50 kV AC, 60 Hz, OCS,	1984	53 km

Type	System Name	Location	Traction Power Characteristics	Launching	System Length
HSR	Tōhoku Shinkansen	Japan	25 kV AC, 50 Hz, OCS	1982: first portion 2010: full line	674.9 km
	LGV Sud-Est	France	25 kV AC, 50 Hz, OCS	1981	409 km
	Amtrak Acela	New England, US	25 kV, 60 Hz; 12.5 kV, 60 Hz; 12 kV, 25 Hz; OCS	2000	735 km

The inconsistency across project typologies and the technical choices made by designers underscores an important point on this topic: not all electric railway projects within the same category are addressed with the same technical solution. This observation and its implications will be further explored in Section 3.3, which presents gaps in standards and codes for railway electrification.

3.2 Selected Projects Analysis

For the gap analysis, five ongoing international railway electrification projects with different applications were selected. The analysis focused on the codes and standards used in the design of the different systems and identified potential gaps in the North American context. Table 4 presents the five selected projects and the standard frameworks used, showcasing their variety.

3.3 Identified Gaps in Railway Electrification Standardization

This section presents the gaps in railway electrification standardization that were identified through the literature review and gap analysis. The full list of standards that were studied is provided in Appendix A.

3.3.1 Standardization Gaps in Traction Power Components

3.3.1.1 Traction Power Substations

TPSS are critical infrastructure components in electrified rail systems, responsible for converting and distributing electrical power to the network that powers vehicles via overhead catenary or third rail systems. Their design, operation, and integration directly impact system reliability, safety, and lifecycle performance. In the North American railway electrification context, the literature review and engagement with interested parties revealed several standardization gaps related to TPSS that affect the design and development of electrified rail systems. Specific applications, such as HSR and freight rail, are affected by gaps related to incomplete local frameworks available for the design of electrified systems, and other technical issues have also been identified. Appendix A lists all standards applicable to TPSS in the Canadian context.

A 2025 report by the Federal Railroad Administration (FRA), Cost and Benefit Risk Framework for Modern Railway Electrification Options, includes the following insight regarding the state of freight rail electrification in the US: “Without a sustained freight rail electrification industry, there is a lack of best practices and proven, standard ‘off the shelf’ designs and approaches for US mainline freight applications” [5, p. 77]. The absence of a mature domestic industry has led to limited institutional knowledge, standardized solutions, and replicable models for electrifying freight rail at scale. The FRA report also highlights the need for foundational work in developing frameworks, technologies, and partnerships to support future electrification efforts. Technical challenges linked to the lack of standardization are mentioned, including “the continued conflict between AC electrification and DC track circuits, and uncertainty in the exact clearance requirements for the 50 kV electrification” [5, p. 64]. While the report presents some technical solutions regarding these issues, it primarily focuses on the cost and the risk-benefit framework for the general electrification of railway in the US [5].

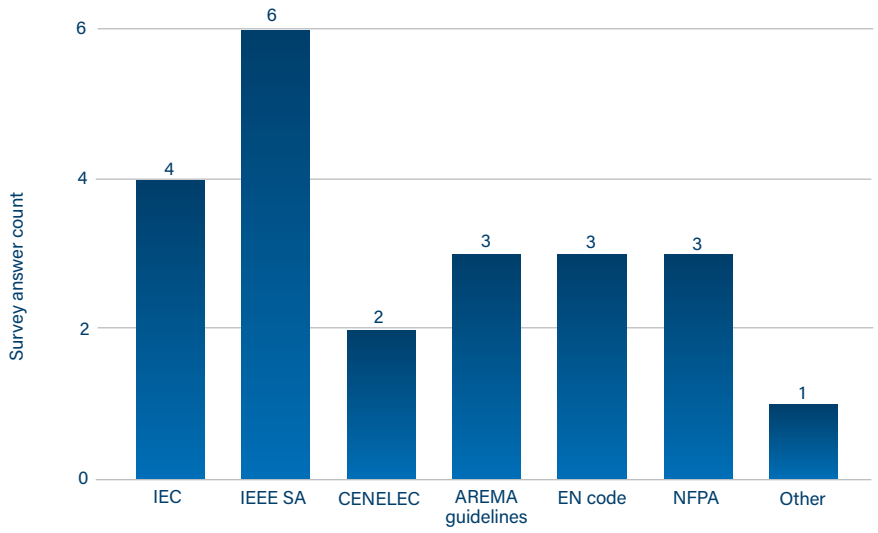
Table 4: Selected Rail Electrification Projects and Their Respective Standards Frameworks

Project	Application	Traction Power Characteristics	Most Recent Construction	Standard Framework
REM (Montreal, Quebec)	LRT	1,500 V DC, OCS	Ongoing: started in 2020 First section in operation since 2023	Design specifications [43] are based on: ▪ IEC ▪ Hydro-Québec ▪ CSA ▪ CEN–CENELEC ▪ IEEE ▪ NFPA
GO Expansion (Ontario)	Commuter rail	25 kV (2x25 kV), AC, 60 Hz, OCS	Ongoing: development phase started in 2022 [44]	Metrolinx guidelines [45], [46] are based on: ▪ Ontario Electrical Safety Code ▪ CSA Standards ▪ AREMA ▪ Ontario Building Code ▪ IEC ▪ IEEE ▪ CEN–CENELEC
Edmonton LRT (Edmonton, Alberta)	LRT	600 V DC, OCS 750 V DC, OCS (Valley Line)	Ongoing: started in 2021, Valley Line West	Design guidelines for traction power [47] are based on: ▪ AEUC ▪ CSA ▪ NFPA ▪ IEEE ▪ ASTM
California High-Speed Rail (California, US)	HSR	25 kV (2x25 kV), AC, 60 Hz, OCS	Electric system	California HSR design guidelines [48] are based on: ▪ AREMA Manual ▪ CEN–CENELEC ▪ National Electrical Safety Code ▪ IEEE/ASME studies ▪ California Public Utilities Commission General Orders ▪ Union Pacific Railroad engineering standards ▪ Southern California Regional Rail Authority ▪ BNSF Railway
Rail Baltica (Finland, Estonia, Latvia, Lithuania, and Poland)	HSR	25 kV, AC, 50 Hz, OCS	Ongoing: started in 2024	Design guidelines on traction power, OCS, electromagnetic compatibility, and signalling [9], [23], [49], [50] are based on: ▪ CEN–CENELEC ▪ IEEE ▪ UIC

The California High-Speed Authority also noted this gap in its guidelines for the development of its HSR project: "At this time there are no specific North American Federal or State of California standards or criteria for 25 kV 60 Hertz Electrification Systems. AREMA Manual is only recommendatory in nature" [48, p. 830].

Some of the literature indicated that standardization could help lower costs and speed up project delivery for Canadian projects [51]. The variety of available configurations can be confusing [52], and the design of rail electrification (particularly LRT) faces various difficulties in terms of decisions regarding which codes or standards should be followed and adopted. Major rail operators, such as TTC and Metrolinx, have their own standard specifications, design drawing guidelines, and templates [46], but there are gaps when it comes to the detailed design of various electrical systems related to rail electrification, most of which rely heavily on the prevailing codes in the relevant province, which commonly refer to the Canadian Electrical Code (CEC), as applicable [53]. However, there is a gap in the scope of the CEC, which excludes "equipment and facilities that are used in the operation of an electric railway and are supplied exclusively from circuits that supply the motive power" and "installations or equipment used for railway signalling and railway communication purposes and located outdoors or in buildings or sections of buildings used exclusively for such installations" [53]. This limits the available local references and standards framework around TPSS. CAN/CSA-C22.3 NO. 8-M91, Railway electrification guidelines [54], helped to address this gap, but are limited to 25 kV AC railway electrification systems, a traction power system primarily used for HSR or interurban applications. According to some of the interviewees, this resulted in two consequences: (a) these guidelines were mistakenly used in low-voltage applications, and (b) industry representatives understood the limited scope of CAN/CSA-C22.3 NO. 8-M91 and elected to use other international frameworks dedicated to light rail and lower-speed applications. Results from the survey showed that the IEEE and IEC standards are most commonly used, while CEN–CENELEC and other standards are sometimes used in other instances, as shown in Figure 3.

FIgure 3: Frequency that different standards frameworks were referenced in TPSS design according to survey responses.



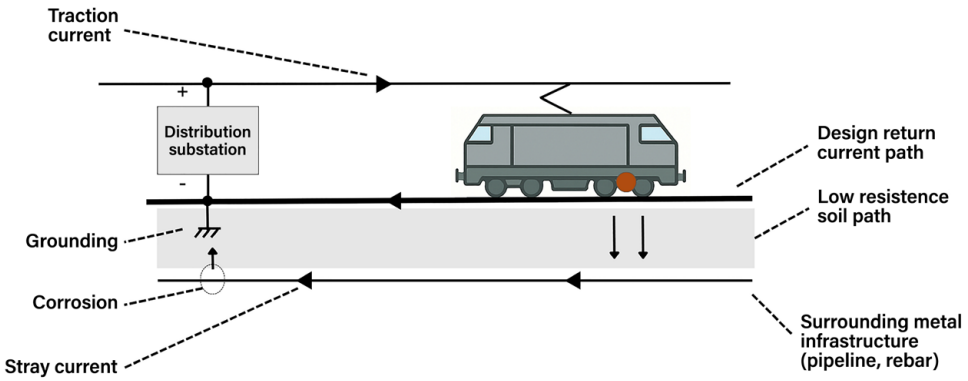
As an example, IEEE standards could be used in transformer rectifier unit design and IEC or CEN–CENELEC standards could be used for TPSS design. A trend was identified in the survey responses that suppliers with European experience tended to use the EN code to guide their design decisions, while suppliers with local experience tended to use the IEEE standards. However, the information collected during the interviews also showed that IEEE standards are used differently than the EN code. Specifically, interviewees indicated that they use the IEEE standards to guarantee the compliance of specific equipment commercialized in the North American market, while they use the EN code to support the design and conception of railway installations, as well as for equipment imported from the European Union [48].

There are other standards specifically intended for the definition of railway traction power supply, including IEC 60850 and EN 50163 [48]. For DC applications, gaps were identified in the existing literature. The IEC 62590 series for electronic power converters and DC power stabilization are still in development, and EN 50328 is being used as the basis for its development. The IEEE 1653 series addresses power rectifying and transformer rectifier units for DC components under 1500 V DC. Engagement with interested parties highlighted the lack of standards for DC systems operating under 3 kV.

IEEE has started several initiatives, such as the IEEE Vehicular Technology Society Traction Power Systems Standards Committee (VTS/TPSSC), which aims to produce relevant content regarding TPSS [55]. IEEE also publishes a Guide for Rail Transit Traction Power Systems Modeling. In terms of standards, the IEEE C57 series applies to dry-type and liquid-filled transformers [56].

In addition to the gaps identified in the literature, the engagement with interested parties highlighted several technical and operational challenges related to TPSS that are not well addressed by existing standards. Of these, the foremost gap is the lack of harmonized guidance on grounding, bonding, and stray current protection, particularly for DC traction systems, as illustrated in Figure 4. Projects such as the Ontario Line and the new REM system developed specific frameworks to manage risks linked to stray current, emphasizing the need for clearer design criteria and lifecycle inspection standards.

FIgure 4: Illustration of stray current in DC systems.





Furthermore, the need to certify European-sourced TPSS equipment, which often lacks CSA or UL certification marks, presents a major cost and timeline burden. Interviewees cautioned that any new Canadian standard must avoid imposing additional certification requirements that limit market access. Finally, participants noted that confusion remains over the application of the electrical code, standards, and building regulations, which compounds the design of entire power substations, especially in complex retrofit or shared-infrastructure projects. These insights point to the need for a coordinated, application-specific standard that improves safety, supports interoperability, and reduces ambiguity without increasing the labour burden on transit agencies and suppliers.

Overall results from the engagement revealed four critical standardization gaps related to TPSS in the Canadian railway electrification context. First, there is no dedicated Canadian standard for TPSS design and operation, leading to a patchwork of AREMA, IEC, IEEE, CEN–CENELEC, and CSA standards being selectively applied, often inconsistently, across projects. This lack of harmonized guidance contributes to confusion over design criteria, particularly for DC systems under 1.5 kV, which are common in LRT applications but not adequately covered by existing standards. Second, there is a persistent gap in clear, codified requirements for grounding, bonding, and stray current mitigation in DC TPSS, despite these being identified by the industry as a major source of infrastructure degradation over the project lifespan. Third, the absence of certification alignment between North American (CSA/UL) and European (EN) standards imposes barriers for the use of proven equipment manufactured in the European Union. Finally, jurisdictional ambiguity between utility codes, electrical standards, and building regulations creates delays and risks in permitting, particularly in retrofit or shared-infrastructure contexts. These gaps highlight the need for unified TPSS guidance that describes an approach that is application-specific, safety-oriented, and compatible with international supply chains, while reducing regulatory and cost burdens on project proponents. Pathways to address these gaps could include describing the application of existing international standards, collaborating with international standards organization and committees, or developing a Canadian standard.

3.3.1.2 Power Transmission and Distribution Systems

Power transmission and distribution systems are important in rail electrification because they carry electrical power from the TPSS to the contact systems. Regulation and standardization of these

systems are key to support reliability of operations and protection of equipment and people. However, although several relevant international and regional standards are available, significant gaps exist in the standardization landscape for these systems, including regulatory misalignment, grid compatibility challenges, limited guidance for field deployment, and scope limitations (particularly for DC systems and mixed-use rail environments), highlighting the need for harmonized, context-specific frameworks applicable to Canadian rail electrification.

Among the key standards referenced for power transmission and distribution systems, the CEC was identified as the most frequently used, even though it excludes railway installations from its scope [53]. Industry engagement revealed that the CEC is frequently used as a basis for the conception of power transmission installations, including insulation protection and cable sizing. This illustrates the gap left by the CEC in terms of electrical installation design for traction power installations.

Results from the survey showed that IEC standards, particularly IEC 60850, are widely used to define voltage and frequency parameters for railway power supply systems. IEC 60850 provides detailed specifications for voltage levels and operating conditions, but primarily in the context of 50 Hz systems, which align with the European grid. While it mentions other frequencies, such as 16.7 Hz or 60 Hz, the guidance for 60 Hz is less robust and lacks precise frequency limits for systems operating at 60 Hz, which is the dominant frequency in North America. This creates a gap in applicability and clarity for railway power supply design in the North American context. In addition to IEC 60850, IEC 62236 is also commonly used to ensure electromagnetic compatibility and compliance with environmental conditions.

IEEE also provides guidelines and standards to address certain components in DC and AC applications, with a collection on the topic of switchgear, circuits, and fuses listing a total of 89 active standards, guides, recommended practices, and corrigenda [57]. Since 2015, IEEE has published several standards for DC in power distribution and transmission, such as IEEE C37.14 for DC breakers, IEEE C37.20.1 for DC switchgear, and IEEE 1627 for transient overvoltage protection in DC with surge arresters. All of these publications cover either DC or AC applications from the design and manufacturing perspective, but only IEEE C37.20.1 addresses DC traction power, and it is insufficient. It should be noted that in the literature, similarities between IEC and IEEE standards have been identified, particularly for medium voltage switchgear [58], [59], because harmonization efforts have been conducted by IEEE to align with IEC and vice versa. These efforts are also exemplified by the IEC/IEEE Joint Development Agreement, which was signed in July 2008, for joint development or revision of standards.

APTA publications primarily focus on rail transit systems and public transport, excluding heavy rail and commuter rail. APTA RT-FS-S-006-03, which focuses on inspection, maintenance, and testing, explicitly states that it "does not apply to commuter railroads that operate on the general railroad system regulated by the Federal Railroad Administration" [60]. Generally, it is limited in scope to cable inspection of DC systems between 600 V and 1.5 kV, and AC systems above 600 V AC, which implies that systems from 1.5 kV to 3 kV DC are not included. The literature review of APTA guidelines and documents highlighted a strong focus on DC power installations (including power backup, power distribution, OCS, and third rail). Because one of APTA's missions is to support the needs of public transportation [61], most of its resources are designed to address these needs first, particularly maintenance training needs for transit rail systems.

The research conducted for this report identified four significant gaps in the power transmission and distribution of electrified rail systems. First, the CEC is widely used as a design basis, but it explicitly excludes railway applications, leaving engineers to extrapolate from non-specific guidance. Second, while IEC standards, such as IEC 60850 and IEC 62236, are commonly used, they are not fully adapted to the 60 Hz grid prevalent in North America, particularly with respect to defining voltage tolerance parameters and power quality expectations. Third, although IEEE has made progress with AC- and DC-specific standards and railways applications, the AC standards primarily address design and manufacturing and lack detailed guidance for field deployment and system integration in railway environments. Lastly,

the scope of APTA standards is limited to public transit systems for 1.5 kV and less, and excludes heavy rail and commuter rail regulated under the FRA. Consequently, the available documentation leaves a notable gap in coverage for DC systems operating between 1.5 kV and 3 kV, which is relevant for both legacy and modern systems internationally.

These persistent gaps highlight the need to develop harmonized and rail-specific standards that reflect Canadian electric grid conditions, support safe and efficient system integration, and extend beyond transit to include heavy and commuter rail, ensuring that modern electrification projects are guided by clear and applicable frameworks.

3.3.1.3 Overhead Catenary Systems

OCS deliver continuous electrical power to trains through a network of cables designed for pantograph contact. These systems include wires, supports, insulators, and tensioning devices that must perform reliably under diverse environmental and operational conditions. Due to their critical role and exposure to harsh climates, the design, installation, and maintenance of OCS components must follow rigorous standards to ensure interoperability, minimize disruptions, and extend asset lifespans, particularly within the context of Canada's varied climate and expanding electrification needs. This section examines gaps in the OCS standardization landscape, including limitations in the scope of existing Canadian and US design standards, the absence of guidelines addressing operational and evolving climate conditions, and a lack of standardized tools and accredited workforce for OCS installation.

OCS Design

CSA Group has developed a range of standards and guidelines for the design of overhead power lines, including CSA C22.3 NO. 1 [62] and its reliability-based counterpart, CSA C22.3 NO. 60826 [63], which provide general design criteria for overhead power systems. For railway-specific applications, CSA C22.3 NO. 8-M91 [54] offers guidance on OCS design, but it is limited to AC installations with voltages of 25 kV and above, leaving a gap for lighter transit systems that operate below this threshold.

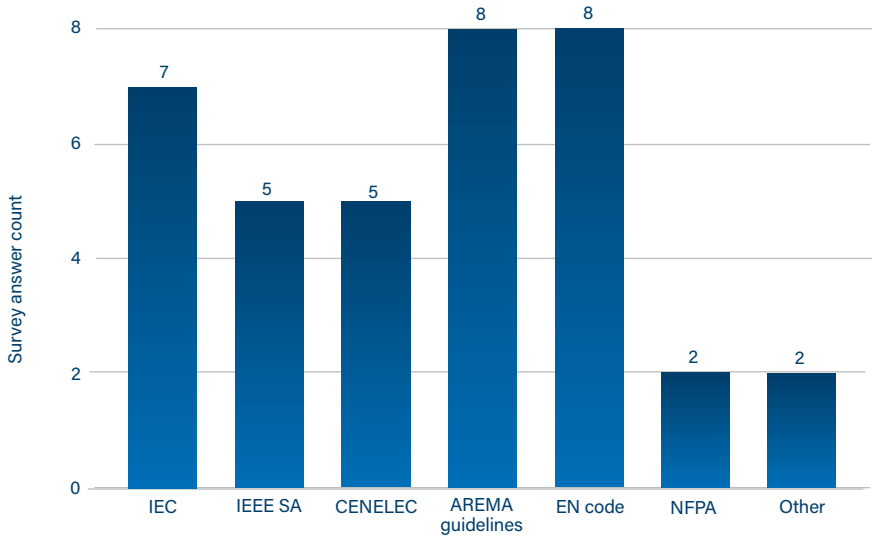
In the absence of comprehensive national standards for lower-voltage rail electrification, designers often rely on international guidelines while ensuring compliance with applicable Canadian codes. These gaps are sometimes addressed locally through provincial or municipal regulations. For example, the Alberta Electrical Utility Code (AEUC) includes detailed clearance requirements for wires and infrastructure that are adapted to suit the province's transportation systems [64]. The AEUC was ultimately adopted as a reference in the design guidelines for the Edmonton LRT, helping to fill the national standardization void [47].

The industry engagement process showed that international standards (IEC, AREMA, and CEN–CENELEC) are preferred as guidance for OCS, as they were more frequently mentioned in the survey results, which are shown in Figure 5.

The REM standard framework analysis, presented in Table 4, showed that the EN code was preferred over the IEC on two occasions: (a) in insulating synthetic rope assemblies for the support of overhead contact lines, EN 50345 was used because it offers broader focus on fixed installations and electric traction compared to IEC 62724, which is more specific to the use of these ropes in supporting overhead contact lines, and (b) for electric traction overhead contact lines, EN 50119 was preferred to IEC 60913, potentially because the IEC code was only updated in 2024, and EN 50119 was the newest available document at the time.

In the US, several gaps were identified in the AREMA guidelines during the literature review and highlighted again during the industry engagement. The most frequent gaps were related to OCS design and clearances, which, for the California HSR project, required the intervention of the California Public Utilities Commission, as highlighted in the Association of American Railroads report on freight rail electrification: "CPUC undertook a lengthy, multi-year process of modification and supplementation of their regulations to account for the different (generally reduced) clearances needed for 25 kV railroad electrification" [65], which showcases the gap in the existing AREMA guidelines.

FIgure 5: Frequency that different standards frameworks were referenced in OCS design according to survey responses.



Furthermore, OCS-related standards published by IEEE focus on the design of DC OCS systems and the maintenance procedures for OCS components for all systems. However, the design of AC OCS for rail transit systems is not addressed.

Maintenance and Inspection of OCS

Maintenance and inspection of OCS can be performed by the rail systems operators or external contractors. Maintenance companies can use their own techniques and tools, including vehicles, drones, or specific monitoring systems to comply with the performance requirements defined by their client.

Existing standards for the maintenance and inspection of OCS are fragmented and limited in scope. For example, section 9.18.2 of CSA Z463, *Maintenance of electrical systems* [66], references APTA RT-FS-S-006 [60], which outlines walking and aerial inspection procedures. While it provides general recommendations, such as vegetation removal and line cleaning, it lacks detailed prescriptions and inspection points, such as tension monitoring, measurements of clearances, wire thickness, stagger, and height. Moreover, APTA standards exclude commuter rail and other non-transit applications, limiting their applicability in other rail systems.

Although there are guidelines that offer a foundational approach to OCS inspection, they are limited in number and are not comprehensive. APTA's focus remains on component-level maintenance within electrified transit systems, rather than providing full maintenance standards. As a result, transit agencies rely on maintenance practices from the general electrical code, and the experience of their own workforce or that of contracted third parties, which further illustrates the gap in standards for OCS maintenance and inspection.

OCS Operating and Climate Conditions

During the interviews, concerns were raised that current Canadian standards, particularly CSA C22.3 NO. 1 and its associated climate loading tables, result in overdesign of OCS infrastructure in cold-weather regions. Participants noted that the design guidelines for anchor and pole structures, particularly those addressing ice and wind loading, do not consider the real usage conditions, maintenance practices, and reaction time for maintenance during extreme climate events. For example, CSA C22.3 NO. 1 [62] guidance treats ice accumulation as a persistent environmental condition for anchor design, whereas European standards, such as EN 50119, consider such buildup an indicator of maintenance failure, not a

design basis, thereby promoting leaner, performance-based infrastructure with other fail-safe mechanisms.

Similarly, a mismatch was noted between CSA Group climate classifications and the actual weather risks experienced by transit systems, with participants advocating instead for more granular and operationally grounded climate criteria, such as those based on the Köppen classification method. This feedback emphasizes two gaps. The first is a lack of standard operating conditions for Canadian rail and transit systems in typical and extreme climate conditions, and the second is the need for design standards that better reflect regional climate conditions and associated recommended operations and maintenance capabilities. This gap currently leads to design burdens without necessarily improving reliability.

OCS Installation Tools and Workforce

Interviewees also highlighted that the construction of OCS in Canada is often constrained by limited domestic availability of specialized installation tools and equipment. For example, catenary wire stringing machines, tensioning devices, and mast alignment tools, all of which are commonly used in Europe, must be imported and adapted to meet Canadian safety standards and to perform reliably in harsh winter conditions. This reliance on foreign-sourced tooling not only leads to higher costs and longer lead times but also requires certification processes that can delay project delivery. Additionally, restrictive union regulations and workforce limitations were cited as a barrier to efficient deployment, as only certain trades may be authorized to operate or maintain specialized machinery. These constraints are particularly impactful in new-build projects or in regions without previous electrification experience, where local contractors may lack both the equipment and the expertise to install OCS. As a result, electrification projects risk delays and budget pressures if procurement and training strategies for specialized tools are not addressed early in the project lifecycle.

The literature review and industry engagement revealed six key gaps in the standardization of OCS for railway electrification in Canada. First, CSA C22.3 NO. 1 [62] and C22.3 NO. 8-M91 [54] do not adequately cover low voltage DC or transit-scale applications under 25 kV, leaving light rail and other transit systems without a suitable national reference. Second, there is no comprehensive Canadian standard addressing the design of AC and DC OCS across voltage classes, especially for commuter and freight rail applications. Third, maintenance and inspection procedures remain fragmented, relying on limited content from CSA Z463 [66] and APTA guidelines [60], which exclude commuter rail and offer general rather than prescriptive guidance. Fourth, there is misalignment between CSA climate loading criteria and operational realities, particularly regarding ice and wind assumptions. Fifth, there is no nationally recognized climate classification framework to guide OCS design, leading to inconsistencies in how projects interpret and apply environmental loading. Sixth, interoperability and supply chain limitations persist due to a reliance on European tools and technologies not readily available or certified for Canadian use. This lack of local tooling, combined with union restrictions and workforce capability gaps, adds time, cost, and risk to project implementation. Together, these gaps emphasize the need for a dedicated, performance-based Canadian OCS standard that reflects local climatic conditions, expands coverage to include DC and transit applications, and supports streamlined procurement and maintenance practices.

3.3.1.4 Grounding and Bonding

In electrified railway networks, grounding (or earthing) and bonding parts and systems are required for safety, system reliability, and stray current or induced voltages mitigation. The research conducted for this report showed that while standards applicable in Canada primarily address AC systems, they offer limited guidance for modern DC applications, which are becoming increasingly common in urban transit. Existing frameworks also lack harmonized voltage-specific requirements, surge protection standards, and coordinated approaches for cohabitation with adjacent infrastructure. These gaps currently affect the project development phase, the implementation of newer infrastructure, and the lifecycle of installations. Solving these gaps with standardization will support safe and efficient deployment across diverse rail environments.



"The research conducted for this report showed that while standards applicable in Canada primarily address AC systems, they offer limited guidance for modern DC applications, which are becoming increasingly common in urban transit."

Design of Grounding and Bonding Systems

APTA provides standards for the inspection and maintenance of equipment, including ground detection systems, in both DC and AC, and stray current corrosion control equipment. As with most APTA publications, these standards are designed primarily for transit systems, supporting the development and implementation of maintenance procedures rather than new design standards.

IEEE addresses DC systems more directly, with IEEE 1653.6 providing recommended practices for grounding in traction power distribution facilities, and IEEE 2720 offering guidelines for rail potential management in DC systems. When introducing IEEE 2720, the IEEE committee acknowledged that "at the time this standard was developed, there were no directly applicable standards, codes or guide documents in the US that addressed permissible rail-to-ground voltages (rail potential)" [67]. This highlights the lack of national frameworks for safe and effective grounding in DC-electrified transit networks.

For AC applications in Canada, CSA 22.3 NO. 8-M91 [54] outlines approaches to grounding at 25 kV AC, and IEEE 80 remains the principal reference for grounding of substation infrastructure. However, participants raised significant concerns regarding the practicality and appropriateness of the CSA Group guidelines, particularly when applied in urban environments or, incorrectly, to DC systems. The "three-zone" grounding model (0–10 m, 10–50 m, and 50–250 m from the rail) from CSA 22.3 NO. 8-M91 [54] is seen as overly prescriptive and challenging to implement, particularly in constrained right-of-way or retrofit contexts. Interviewees emphasized that these requirements are frequently misapplied to DC TPSS, leading to costly overdesign, coordination issues with other systems, and long-term corrosion and lifespan reduction. Experts also mentioned grounding and bonding design errors that were identified during pre-concrete pouring inspections, which required corrections to prevent future stray current damage to embedded rebar and adjacent infrastructure.

In contrast, EN 50122, supported by IEC 62128, offers voltage-specific and functionally-based grounding principles, with greater adaptability to system type and operational environment. These standards also address the design and installation of protective measures in DC systems, which are absent from CSA 22.3 NO. 8-M91 [54]. Furthermore, IEC 62497 supports insulation coordination, while IEC 62848 covers surge protection for DC installations using surge arresters and voltage limiting devices. However, as noted in IEEE 1627, there is currently no North American standard for voltage limiting devices, leaving practitioners reliant on EN 50526, which highlights another regulatory gap for modern TPSS systems.

Grounding and Bonding in Infrastructure Corridors

Utilities and rail operators highlighted persistent and often underappreciated challenges related to stray current, induced voltages, and grounding interactions between electrified railway infrastructure and adjacent power and telecommunications systems. These issues are particularly acute when rail lines and OCS systems run close to high voltage transmission corridors, telecoms infrastructure, or legacy rail signalling systems. For example, fault protection mechanisms on existing rail lines have been shown to be insufficient in protecting assets and personnel during fault events of neighbouring electrified rail corridors or transmission and distribution lines. These risks increase when grounding systems lack proper coordination between domains, such as when rail neutrals are not electrically isolated from utility neutrals, or when equipment grounding conductors are bonded to inadequately protected equipment.

Recognizing these risks, AREMA revised its standards in 2020 to strengthen requirements around the protection of communication equipment, addressing the increasing incidence of interference and surge-related damage caused by energy corridors near electrified rail. However, interviewees indicated that no equivalent national guidance exists to address cohabitation risks across different infrastructure types. The lack of harmonized standards or planning frameworks to help manage induced current and electromagnetic compatibility across co-located systems creates difficulties for standardizing installations. Interested parties called for clearer rules, design criteria, and shared planning protocols to anticipate and mitigate infrastructure interaction risks during project development and lifecycle operation.

Overall, the interviewees agreed that Canadian standards must evolve to offer practical, context-sensitive grounding and bonding guidance in rail applications where there is a risk of stray current and arc flash. A harmonized, application-specific standard that incorporates inspection, lifecycle maintenance, and protection practices was identified as critical for improving TPSS reliability, safety, and cost control.

The literature review and industry engagement regarding the current framework for grounding and bonding in railway electrification revealed five critical gaps, particularly for DC applications and under 25 kV systems. First, Canadian standards, such as CSA C22.3 NO. 8-M91, primarily address AC systems and provide limited guidance for modern DC applications, which are becoming increasingly common in urban and light rail contexts. The three-zone grounding model presents limitations in its application, particularly in space-constrained environments where it can lead to overdesign, construction conflicts, and stray current risks. Second, there is a lack of harmonized voltage-specific guidance for DC grounding and bonding design. While IEEE 1653.6 and IEEE 2720 provide partial coverage, and EN 50122 and IEC 62128 offer adaptable and functional standards, there is no unified Canadian standard incorporating these principles for consistent application. Third, surge protection and insulation coordination for DC systems remain under-regulated in North America, with no recognized standard for voltage limiting devices and ongoing reliance on European documents, such as EN 50526 and IEC 62848. Fourth, cohabitation risks between railway systems and adjacent utility or telecom infrastructure are poorly addressed in existing standards. Practitioners lack a nationally coordinated planning or mitigation framework for managing induced voltages, stray current, and shared neutral conflicts in co-located corridors. Finally, recent updates to AREMA standards on protecting communication systems have yet to be integrated into Canadian practice. These gaps highlight the need for a harmonized, application-specific grounding and bonding standard in Canada, one that is flexible, risk-informed, and capable of addressing modern safety and interoperability challenges across both new and existing electrified rail systems

3.3.2 Other Standardization Gaps Identified

Beyond the technical gaps related to traction power components and behind-the-metre infrastructure, the research conducted for this report identified five broader systemic challenges that impact railway electrification projects across all phases (i.e., planning, design, construction, operation, and maintenance):

- Absence of comprehensive inspection frameworks for electrified rail systems;
- Limited coordination among interest holders, including utilities, transit agencies, and regulatory bodies;
- Gaps related to workforce expertise and accreditation, particularly in specialized electrification roles;
- Integration difficulties with existing infrastructure, especially in legacy systems; and
- Context-specific challenges unique to the Canadian environment, such as climate, geography, and jurisdictional variation.

These gaps hinder the scalability and consistency of electrification efforts and underscore the need for a cohesive national strategy to align standards, streamline processes, and build capacity across the sector.

3.3.2.1 Optimal Design of Railway Infrastructure

Individual and Company Responsibilities

In both Canada and the US, the conception and technical design of railway infrastructure is led by licensed professional engineers, who are legally accountable for the integrity and safety of their designs. Canadian engineers, regulated under self-governing professional bodies, are obligated to uphold public safety and environmental responsibility while serving their clients and the broader society [68]. In the US, only professional engineers are authorized to sign and seal engineering drawings and offer services to the public, reinforcing this legal responsibility through licensure [69]. However, in the absence of comprehensive Canadian codes or standards specifically governing railway electrification and infrastructure design, engineers are left to rely on a mixture of international standards, past project precedents, and internal risk management practices. As a result, design decisions, particularly those concerning equipment sizing, safety margins, or environmental loading conditions, are approached conservatively. Interviewees explained that firms are subject to oversize components (e.g., power capacity, pole loading, insulation classes) to mitigate liability and ensure regulatory defensibility in the absence of nationally recognized benchmarks. While this practice may reduce legal exposure, it also increases project costs, creates inefficiencies, and can hinder standardization across transit systems.

Reliability, Availability, Maintainability, and Safety Studies

During industry engagement, participants strongly advocated for a more systemic and repeatable approach to design. Rather than approaching each project from scratch, participants emphasized the need for a framework that defines expected operating conditions, maintenance strategies, and system performance objectives from the outset. Establishing such a framework would enable more effective collaboration among those responsible for design, construction, and operations, while also improving long-term maintainability. RAMS studies were identified as a key tool for achieving this. These studies, while not mandated in Canada, are increasingly used to guide design decisions and manage risk across the project lifecycle. Metrolinx has included this practice as part of its system assurance process [70].

Interviewees further noted that EN 50126 and the IEC 62278 series are the primary standards used to guide RAMS processes in Canadian projects, offering a lifecycle-based methodology to define roles and responsibilities between project owners, engineers, and suppliers. In contrast, the IEEE approach to RAMS is more segmented, often integrated into domain-specific standards, such as IEEE P3143 for Maglev systems or within power system design.

A recurring concern identified through the research and engagement phase is the absence of a centralized Canadian guide that consolidates applicable international and local standards for rail electrification projects. This gap has led to a perception among practitioners of having to start from scratch with each new project, resulting in inconsistent application of standards and frameworks. The lack of harmonization has been cited as a root cause of variability across transit agencies and projects, which in turn limits the sharing of lessons learned and reduces the transferability of best practices across the sector.



Climate Conditions Guidance

A frequent theme in the interviews was the need for project-level design to be grounded in real, context-specific environmental and operational conditions. Without national standards for climate adaptation or system configuration, engineering teams are often left to interpret vague or overly generic requirements. For example, general environmental loading tables in CSA Group standards are sometimes applied uniformly across regions with different climates. Interviewees stressed the need for climate-responsive design guidelines, not prescriptive component standards, but adaptable tools that enable consistent assumptions for Canadian geographies, particularly related to temperature, wind, snow, and icing impacts on electrical systems.

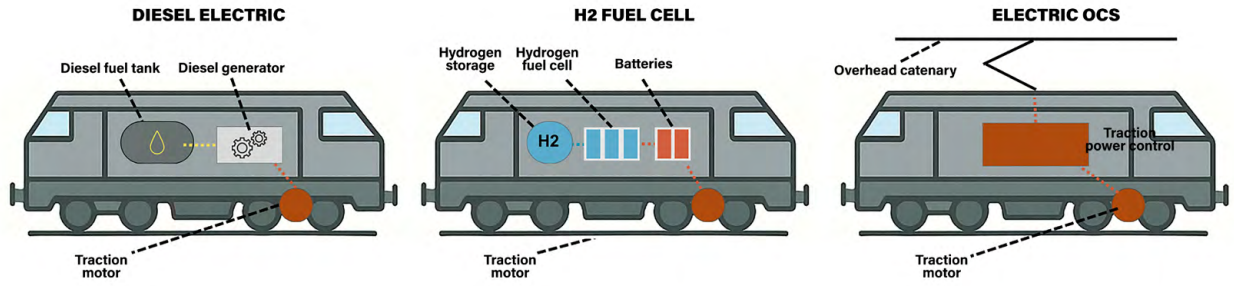
Optimal infrastructure design requires not only competent engineering practice but also a clear, defensible, and repeatable framework. Interviewees highlighted the value of Canadian guidance that does not duplicate international standards but defines their application in local projects and builds upon them to reflect the unique conditions, jurisdictional complexity, and delivery models of rail projects in Canada. This could help reduce overdesign, support cost-effective engineering, and allow agencies to define operational and lifecycle needs more effectively from the outset.

3.3.2.2 Technological Competition in Primary Energy Sources

The decarbonization of the rail sector is supported by a growing array of technologies, from hydrogen fuel cells and battery-electric systems to biodiesel and traditional catenary electrification (three are illustrated in Figure 6). These technologies are often compared without a consistent evaluative framework, leading to fragmented industry perspectives and potentially biased decision-making. This missing piece stresses the need for a framework to compare technologies in the rail electrification sector.

Recent developments in North America illustrate this competition. Demonstration projects for hydrogen fuel cell locomotives have been conducted in Quebec [32] and California [33], showcasing the operational viability of hydrail in different contexts. Meanwhile, industry publications and studies reflect diverging views on the most promising paths forward. For example, a 2020 report from the Canadian Urban Transit Research and Innovation Consortium ranked the top ten technologies for passenger and freight rail [71], and while it included rail electrification, the focus was on energy management systems and energy storage, which were rated low in terms of technology readiness level, cost, and implementation time. In contrast, alternative

FIgure 6: Illustration of select locomotive traction technologies (simplified powertrains).



propulsion technologies, such as hydrail and catenary-free systems, received higher rankings. The report concluded that Canada could "leapfrog" traditional catenary systems by adopting more advanced, socially attractive non-catenary technologies [71].

Similarly, in a 2024 report, the FRA identified battery storage and hydrogen fuel cells as key technologies for achieving net-zero emissions in the US by 2050 [72]. It also highlighted biodiesel as the most viable near-term solution. The FRA also convened experts to discuss the challenges and opportunities of these alternatives, reinforcing the need for structured comparison [26].

The Association of American Railroads has taken a critical stance on electrification. In a 2020 fact sheet, it argued that mandating electrification is not cost-effective due to infrastructure costs, reliability concerns, and service disruptions [73]. A follow-up report in 2025 further detailed the challenges of electrifying Class I railroads in the US and Canada, including the need for new locomotives and the impact on energy demand [65].

In Canada, academic studies in Alberta [74] and the Okanagan Valley [75] have explored hydrail adoption for regional rail. A comparative study by Delphi Group and Pollution Probe evaluated five alternative fuel technologies for rail sector decarbonization, ranking catenary electrification second behind B20 biodiesel, with battery-electric, renewable diesel, and hydrogen fuel cells scoring lower. The study provided key recommendations and highlighted implementation challenges [22].

Ultimately, this fragmented context highlights the absence of a standardized comparative framework for evaluating decarbonization technologies in the rail sector. While various technological solutions, such as hydrogen fuel cells, battery-electric systems, biodiesel, and catenary electrification, are actively being tested and promoted, they are often assessed in isolation or using inconsistent criteria. This lack of harmonization not only fuels division within the industry but also risks misaligned investments and policy decisions.

Although the examples discussed in this section do not directly expose a standardization gap in rail electrification systems themselves, they reveal a broader issue in the sector, which is the need for a structured, transparent framework to compare technologies across key dimensions, such as cost, readiness, operational fit, and long-term sustainability. Such a framework would support strategic alignment, enable fair competition, and guide interested parties toward the most effective pathways for rail decarbonization.

3.3.2.3 Cost Evaluation and Modelling

Capital expenditures are frequently cited as a barrier to the implementation of new electrified railway projects and the retrofitting of existing systems [51], [76], [77], [78]. While not directly tied to the technical components of railway infrastructure, this challenge highlights an important opportunity for standardization. Industry studies and consultations with interested parties consistently point to the evaluation, projection, and presentation of costs as

a recurring source of disagreement, demonstrating the need for more consistent and clear approaches.

While there is broad agreement that capital expenditures are a major challenge in advancing electrified railway projects, perspectives on the issue reveal a notable dichotomy. On one hand, it is repeatedly noted that the capital costs of transportation projects in Canada have been increasing and exceed the cost of public transport in other regions of the world [51], [79], [80], [81]. On the other hand, there is no current framework or guidelines to compare the estimated development costs between projects or between designs of the same project. This absence of standardized methods for financial comparison hinders the ability to identify the most cost-effective solutions and limits the use of common financial indicators to support evidence-based decision-making.

A central factor contributing to the rising costs of transportation projects is the accumulation of inefficiencies in design, procurement, and risk management practices, as well as external constraints. The University of Toronto's School of Cities 2024 report highlights how project costs in the Anglosphere, particularly in Toronto, have escalated well beyond those observed in comparable projects worldwide. The report attributes this increase to several recurring drivers, including overbuilding due to poor design choices, insufficient knowledge retention within public agencies, risk-averse procurement and risk management practices, and the influence of external constraints [51]. Together, these factors inflate capital expenditures and make it increasingly difficult to deliver projects at levels comparable to international standards.

The absence of standardized tools for comparing project costs has been recognized internationally, and several agencies have developed frameworks to address this gap. In the US, the FRA published guidelines for project sponsors and partners that outline best practices for planning, developing, and presenting the costs of railroad capital projects from planning, development, and implementation [82]. Similarly, in France, the public agency Cerema (Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement) has developed a standardized cost breakdown that categorizes project expenditures into 19 groups [83]. This framework not only enables the assessment of investment costs based on feedback from comparable projects but is also used in national project calls by the Ministry of Ecological Transition to ensure transparent and consistent cost comparisons. These international examples demonstrate how similar tools could be adopted in Canada to support more reliable cost evaluations and guide investment decisions in rail electrification projects at the national, provincial, or territorial level.

Some financial models have already been developed for specific applications in railway electrification, reinforcing the need for more comprehensive tools to guide cost analysis and decision-making. For example, the FRA has reported on the Cost, Uncertainty, and Risk of Railway Electrification with New Technologies model, created by researchers at the University of Texas at Austin. This framework applies a risk-based economic approach to help railroads evaluate electrification investments and to inform further supplier research and development [5]. The challenges identified through this model underscore the complexity of comparing electrification costs across different technologies. Similarly, the Delphi Group and Pollution Probe have recommended that cost models be adapted to better reflect the realities of electrified railway projects [22]. Together, these contributions highlight both the progress made and the gaps that remain in providing reliable financial tools for project evaluation.

In line with industry and consulting studies, cost models must evolve to keep pace with the rail sector's transition toward decarbonization. Rising project costs, the absence of standardized comparison tools, and the limitations of existing financial models all point to the same conclusion: traditional approaches centred on fuel efficiency for legacy railways are no longer sufficient. There is a need for standardized, transparent methods that capture the full lifecycle costs of electrified systems and allow for meaningful comparisons across projects and technologies. Establishing such a framework will not only improve the consistency of cost modelling and presentation but it will also strengthen decision-making and guide more strategic, future-proof investments in rail infrastructure.

3.3.2.4 Inspection and Maintenance

In addition to the technological and infrastructure challenges that catenary-electric railways present for railway decarbonization in Canada, there also significant gaps in regulatory frameworks related to the safe operation, inspection, and maintenance of electrified systems. The literature warns that high voltage catenary systems, while effective for reducing emissions, introduce new occupational and public safety risks that are not fully addressed by Canadian standards. As one study notes, "High voltage catenary systems can pose significant safety hazards for yard workers. . . Safety standards for staff and the general public, as well as education campaigns, would be required" [22, p. 114]. At the time of writing, no Canadian standard or framework addresses the full scope of safe operation, inspection, and maintenance for electrified traction power systems. Table 5 provides details about the two key CSA Group inspection and maintenance standards that have been published on the topic.

Interviews with representatives from transit agencies and engineering firms confirmed the lack of a comprehensive Canadian resource for the ongoing operation and maintenance of electrified railway infrastructure. Instead, rail operators must develop their own internal inspection and maintenance procedures, drawing from fragmented guidance in existing standards. People safety was a concern mentioned by several participants, who indicated that provisions for arc flash protection above 600 V DC in the CSA Group and CEC frameworks were inadequate for installations operating at 750 V DC. This results in inconsistent practices, limited knowledge transfer across projects, and high reliance on the expertise of individual teams, which is particularly problematic for smaller organizations or agencies that lack a legacy network with established processes.

For traction power systems, CSA Z463 [66] is the most directly applicable Canadian standard. It provides some guidance on general electrical maintenance and includes two paragraphs dedicated to OCS, as well as a broader section on TPSS. However, much of the guidance is generic, and the standard largely defers to four APTA standards, which are focused on commuter and LRT systems in the US. These references provide useful but limited insights, especially regarding newer electrification technologies or the complex interfaces between civil, electrical, and signalling systems in modern rail projects.

Interviewees emphasized that operators are left to make case-by-case decisions on maintenance frequency, inspection criteria, and risk mitigation. One challenge that was repeatedly raised is the lack of national protocols for inspection handoffs between contractors and operators in public private partnerships or engineering, procurement, and construction projects, which has led to delayed issue detection and complications during

Table 5: Relevant Canadian Inspection and Maintenance Standards

Standard	Scope	Gaps in Railway Electrification
CSA Z463, *Maintenance of electrical systems* [66]	Specifies requirements for the maintenance of electrical equipment and systems, applicable to both new and existing installations. Focuses on safety, reliability, and loss control.	▪ Does not specifically address railway electrification systems, particularly DC traction power systems. ▪ Lacks guidance for rail-specific maintenance practices and integration with railway safety frameworks.
CSA Z462, *Workplace electrical safety* [84]	Defines workplace electrical safety requirements, including safe work procedures, PPE selection, and training for workers exposed to energized equipment. Based on NFPA 70E and harmonized with the Canadian Electrical Code.	▪ Explicitly excludes railway rolling stock and railway power systems used exclusively for rolling stock operation. ▪ Not suitable for rail electrification environments or traction power safety procedures.

transition to operational phases. In some cases, long-term maintainers have found infrastructure is noncompliant with operational standards or difficult to maintain due to insufficient as-built documentation or inappropriate component selection.

In terms of electrical safety during maintenance, CSA Z462 [84] is used as a baseline reference by many operators. Although it does not formally apply to traction power systems, some hazards (such as shock or arc flash risks) are translatable. However, findings from both the interviews and the literature review indicated a gap in CSA Z462 [84] related to DC arc flash protection [85]. Specifically, Table 6B lacks coverage of voltages between 600 and 3,000 V DC, which are typical in transit TPSS installations. This leaves technicians and safety personnel with no exact standard to assess DC arc flash hazards in these voltage ranges, forcing them to adopt safety measures from a general standpoint and a piecemeal of vendor recommendations, international guidelines, or conservative assumptions.

Compounding these challenges is the unclear role of inspection authorities. In provinces such as Ontario and British Columbia, provincial safety agencies like ESA and WorkSafeBC may be called upon to inspect TPSS or OCS infrastructure. However, as the CEC explicitly excludes railway traction power systems, such authorities lack a clear regulatory framework to guide their assessments [53]. Inspectors may resort to using the CEC, supplemented with local codes, but the absence of rail-specific inspection protocols can lead to incomplete evaluations, inconsistent enforcement, or even regulatory uncertainty that delays commissioning.

The research conducted for this report highlighted a critical need for standardized, nationally recognized inspection and maintenance protocols for railway electrification systems. Such protocols should clearly define responsibilities, reference applicable voltage classes and technologies, and include lifecycle considerations for both infrastructure owners and regulators. Without this, Canada's electrification efforts risk operational inefficiencies, safety oversights, and a loss of consistency and knowledge sharing across transit agencies and jurisdictions.

3.3.2.5 Labour Training

Interested parties also highlighted a significant gap in specialized training programs for railway electrification in Canada. While general railway operations training exists, there is an absence of curricula focused on the design, construction, and maintenance of electrified rail systems. This deficiency, which is also highlighted in the FRA study on freight rail electrification [5], poses a barrier to the development and implementation of electrified rail projects because the workforce lacks the necessary skills and experience in installing and maintaining such systems. Several studies on the labour market have highlighted the need for green skills and green jobs in the transportation sector [86], [87], [88]. While these studies specifically target skills and jobs related to road transportation decarbonization, given the role of railways in Canadian freight transport and their potential for decarbonization, the rail sector could benefit from this transition as well. Railway training in Canada tends to focus on train operators and yard maintenance crew training, with curricula and pathways provided by educational organizations, but also through internal training by rail companies [89], [90], [91], [92].

In the US, the Sierra Club has pointed out the limited availability of specialized university programs in railroad transportation and engineering, noting that only three such programs exist nationwide [21]. Similarly, in Canada, while institutions such as the British Columbia Institute of Technology offer railway training programs, they are primarily geared toward conventional rail operations and do not extensively cover electrification aspects [92]. However, some progress is being made to address this gap. For example, Ontario Tech University launched a railway engineering specialization program in September 2025, which includes courses on railway systems, safety and signalling, rolling stock, and operations and maintenance [93]; and McMaster University offers a course on railway electrification infrastructure and technology, which covers principles of railway electrification, overhead catenary systems, and power supply for electric trains [94].

Despite these developments, interviewees emphasized the need for a more comprehensive and coordinated

approach to training. They advocated for national standards and certification programs to ensure consistency and quality in training across the country. Furthermore, integrating railway electrification topics into existing green jobs and sustainable transportation training initiatives could help build a workforce equipped to support Canada's transition to a low-carbon economy.

3.3.2.6 International Collaboration

Although railway electrification efforts are advancing in Canada, the US, and Mexico, interview participants widely agreed that the lack of formalized international collaboration remains a major barrier to the efficient and harmonized development of electrified rail infrastructure in North America. This was emphasized in both the interviews and in the literature: "Given the significant infrastructure requirements for alternative propulsion technologies, and the interoperability of railways across North America, some degree of alignment across Class 1 railways operating in Canada, the US, and Mexico is essential" [22, p. 53]. However, competition, proprietary technologies, and institutional silos often limit knowledge sharing between jurisdictions and operators.

Interviewees noted that, unlike Europe, where the CENELEC–IEC partnership, formalized in 2016, ensures that nearly 80% of CENELEC standards are aligned with or directly based on IEC publications [95], North America lacks a central body that coordinates railway electrification standards at the continental level. EN standards are also coordinated with CEN–CENELEC to be adopted by CENELEC's 34 member countries. In Europe, this harmonization has enabled widespread interoperability, repeatability of design, and transnational integration, while also reducing cost and procurement complexity. The absence of a similar approach in Canada means that projects are often guided by a patchwork of AREMA, IEEE, IEC, CEN–CENELEC, and CSA Group standards, with decisions made at the project or agency level rather than being aligned nationally or binationally.

For Canada, collaboration with AREMA is particularly important due to the dominance of Class I freight railways and the need to manage shared corridors and infrastructure interfaces, especially in urban commuter and regional rail settings. Interviewees flagged that in many cases, commuter rail electrification projects must coexist with freight rail systems governed by AREMA standards, particularly when it comes to grounding and bonding, signalling, and communications infrastructure. Misalignment in these areas has led to delays and costly redesigns, especially in projects where early coordination with freight operators was lacking. As previously noted, several initiatives from Transport Canada, such as its memorandum of understanding with the Railway Association of Canada [35], and its Rail Decarbonization Task Force collaboration with the US Departments of Energy and Transportation, both of which could be leveraged to align on standardization.

Interviewees also agreed that light rail and HSR systems that are physically separated from Class I freight infrastructure could be more freely standardized at the national or local level, using existing international frameworks adapted for Canadian conditions. This division of networks allows for parallel standardization strategies: one pathway harmonizing with US practices for shared-use freight rail systems and international/legacy railways, and the other based on international standards enabling selection and customization according to the needs and gaps of isolated systems such as LRT and national HSR.

A recurring concern raised in the interviews was Canada's limited participation in international standardization bodies, particularly in IEC technical committees such as TC 9, which governs electrical equipment and systems for railways. At the time of consultation, only one Canadian expert was participating in the TC 9 subcommittees relevant to traction power and OCS design [96], [97]. This underrepresentation means that Canadian climatic conditions, operational realities, and safety expectations are often not reflected in the resulting international standards, which can lead to inappropriate or costly adaptations during local implementation. However, it should be noted that Canadian experts and interested parties have been more active in IEEE committees, particularly within the IEEE VTS/TPSSC. Formed in 2002, this committee brings together public and private sector leaders in electrified transit to develop national consensus



"In Canada, the majority of medium- and heavy-duty rail infrastructure used for intercity transportation is owned and operated by private freight rail companies, primarily CN and CPKC."

standards and guides design, manufacturing, testing, and operation of traction power systems. It also collaborates with other organizations, such as APTA and AREMA, and serves as a venue for sharing ideas to improve North American electrification practices [55].

Interviewees expressed a strong desire to see Canada take a more proactive role in shaping international electrification standards, both to reflect its distinct environmental conditions and delivery models, and to better position its domestic rail industry in future procurement and innovation opportunities. They noted that strategic collaboration with US organizations (e.g., FRA, FTA, AREMA) and structured engagement with IEC and IEEE standard bodies will not only improve alignment but will also enhance Canada's influence in shaping standards that affect national infrastructure investment decisions.

3.3.2.7 Mixed-Use Railroad and Neighbouring Installations

In Canada, the majority of medium- and heavy-duty rail infrastructure used for intercity transportation is owned and operated by private freight rail companies, primarily CN and CPKC [98]. This ownership model has long posed challenges for the development of passenger rail services. As a result, proposals for accessing and electrifying portions of this infrastructure remain complex without a clear framework that accounts for both implementation requirements and the operational realities of freight services.

In response to the challenges posed by this model, organizations and advocacy groups, including VIA Rail, have raised concerns that passenger services are deprioritized, resulting in frequent delays and limited reliability [99]. In 2023, MP Taylor Bachrach introduced Bill C-371, *An Act to amend the Canada Transportation Act (passenger rail service),* which mandated the prioritization of passenger trains on shared corridors [100]. However, a 2024 Transport Canada study concluded that the associated costs and operational trade-offs for freight rail were too significant, and the Canadian government decided not to pursue the prioritization of passenger rail over freight rail further, instead continuing to focus on its HSR initiative as a more viable alternative [34], [99].

While shared-use of track is less common in LRT systems, the ION LRT project in Waterloo Region is a notable exception, with LRT vehicles operating over sections of track shared with CN freight services. To meet construction timelines and optimize corridor use, the design firm proposed an innovative track-sharing arrangement, the first of its kind in Canada. Inspired by German precedents, this solution required design modifications, custom signal protection systems, and operational coordination between freight and LRT schedules [101], [102], [103]. The integration of light rail with heavy rail systems introduced a new layer of complexity, requiring tailored safety protocols, timetable alignment, and rolling stock clearance standards.

As many interviewees emphasized, these technical and operational challenges are magnified in electrified systems, where electrical infrastructure must be safely co-located with legacy rail, signalling, and communication networks. For example, some participants described experiences where the lack of coordinated grounding and bonding between old and new systems could have led to unintended energization of track components, creating potential hazards for workers and increasing wear on sensitive signalling equipment. Other participants highlighted the absence of a clear framework for managing electrical cohabitation, particularly in corridors shared with high voltage transmission lines or urban distribution grids.

In several cases, TPSS or OCS installations had to be redesigned or repositioned due to interference with surrounding utility easements, underground cables, or electromagnetic-sensitive assets. Interviewees noted the challenges of building or maintaining traction power infrastructure in dense corridors, where legacy utilities or older grounding schemes posed unforeseen risks. These concerns were echoed in the context of rail system faults, as short circuits can energize rails and create unsafe conditions, especially when signal and communication systems use independent grounding schemes. This complicates the application of standards such as NFPA 70E, which presumes harmonized protection systems not typically present in rail corridors.

Despite some early exploration of shared-use rail corridors in North America [104], there is no comprehensive technical guidance for integrating electrified rail systems within mixed-use corridors or adjacent to sensitive utility infrastructure. Most prior research focused on track geometry, operational scheduling, or freight and passenger compatibility, rather than electrification-specific concerns such as stray current (see Figure 4), induced voltage, surge protection, and signal system interactions. Producing a standard or guidelines for the design and integration of such installations could help in the use and conversion of legacy networks or the implementation of newer rail systems in infrastructure corridors.

3.3.2.8 Harmonization Between Provinces

As previously noted, the CEC explicitly excludes railway applications from its scope, particularly for traction power systems and electrified infrastructure. This creates a regulatory void when it comes to designing, inspecting, and operating railway electrification assets. In the absence of clear national guidance, each province or utility authority can interpret and adapt the CEC to fill its gaps. Ultimately, this results in regional differences in how railway electrification projects are designed, permitted, and regulated, which could hinder the development of inter-regional projects.

Interview participants described this as one of the most significant barriers to consistency and reproducibility across projects. In jurisdictions such as Ontario and British Columbia, where provincial safety authorities (e.g., ESA and WorkSafeBC) are tasked with overseeing electrical safety, traction power installations fall into a grey area. Interviewees noted that authorities often default to applying the CEC or related provincial codes, despite these frameworks not being written with rail electrification in mind. This results in inconsistent interpretations, duplicated engineering efforts, and project delays as each authority may impose different inspection requirements or safety thresholds.

This regulatory fragmentation also increases costs by forcing engineering teams to customize designs and documentation for each province, rather than relying on a common design or permitting template. Transit agencies reported that even similar systems, such as 750 V DC LRT traction power or OCS installations, require substantially different technical documentation depending on the local code context.

Despite the challenges, several opportunities for improvement were identified during the industry engagement process. First, and as mentioned in 3.3.2.1, there is support for the development of harmonized national guidance or a technical guideline that outlines how existing codes (such as the CEC) and international standards (such as CEN–CENELEC, IEEE, or AREMA) can be incorporated appropriately into railway electrification projects. Rather than duplicating

existing codes, this guidance would help engineers, regulators, and project sponsors interpret and align their approaches using standardized assumptions, safety thresholds, and lifecycle expectations. Second, harmonized guidance could include templates or decision trees for how to apply codes based on system type (AC vs. DC), voltage class, or interface with public infrastructure. This would reduce the burden on provincial authorities to interpret rail-related installations on an ad hoc basis and support a more predictable permitting and inspection process. Finally, interested parties suggested that federal or pan-Canadian leadership could facilitate cross-provincial working groups with safety bodies to align on inspection, safety, and design practices. Such collaboration would build a foundation for shared learning, standardized project delivery, and cost-effective electrification, especially as more provinces begin to plan for decarbonized rail networks.

4 Recommendations and Opportunities for Standardization

4.1 Strategic Standardization for Scalable Railway Electrification

The evolving landscape of railway electrification in Canada presents a timely opportunity to leverage shared expertise and document best practices that can streamline future projects. Agencies and interested parties have expressed a strong desire for structured guidance rooted in the collective experience of past electrification efforts, both domestic and international. Rather than "reinventing the wheel" for each project, there is a clear benefit in developing and adopting a framework of coherent standards that promote consistency, safety, and efficiency across jurisdictions.

Developing new standards requires a thoughtful and balanced approach. Interested parties cautioned that overly rigid or narrowly defined standards could unintentionally restrict supplier participation and negatively affect transit agencies with limited budgets and technical capacity. To be effective, standards must prioritize practical implementation while fostering harmonization across the industry. They must also be flexible enough to accommodate proven international solutions, which will reduce barriers to adoption or market access. The recommendations for standardization presented in this report were formulated with the following characteristics in mind:

- Be clear and actionable, using recognized approaches and well-defined terms, roles, and responsibilities for all involved parties.
- Include implementation guidance with dedicated guides, annexes, examples, decision trees, or checklists to help practitioners apply standards in real-world contexts.
- Align standards with existing regulatory context and with international practices and standards, to ensure compatibility with provincial codes and utility requirements to reduce friction in all phases of project development.
- Avoid over-prescription and focus on performance-based outcomes by providing tools and standard approaches that ultimately consider operational goals and local factors and aim for long-term performance and climate-resilient operations.
- Support capacity building of the sector with adequate training, certification, and workforce development pathways to ensure that agencies and contractors can have and develop the necessary expertise.

This section examines how standards can act as powerful enablers of collaboration and capacity building in Canada's railway electrification journey. It introduces a set of recommendations across key areas to support a coordinated and scalable transition, including the use and application of existing Canadian and international standards for dedicated systems or applications, operational and performance standardization, economic considerations for standardization, inspection and maintenance framework needs, and workforce training and accreditation.

4.1.1 Build on International Standards for the Canadian Context

Challenges and Gaps

The standardization landscape for railway electrification in Canada is heavily shaped by the application and adaptation of international and European standards. While these standards form the technical backbone of most projects and rely on thorough experience,

certain local operational and environmental realities may be overlooked, requiring retroactive modifications to ensure relevance. This type of gap was noted during the research and is illustrated by the lack of definition for 60 Hz power supply conditions in IEC standards.

Several interviewees cautioned against developing entirely separate Canada-specific standards for railway electrification because it could introduce compliance complications, require costly recertification of equipment, and reduce interoperability across North America. For manufacturers and suppliers operating across the US, the European Union, and Canadian markets, custom standards may disincentivize participation and increase costs, particularly in a sector already constrained by a limited pool of qualified suppliers and labour. As one participant noted, "creating Canadian-only standards may result in more customized designs, compliance issues, and a lack of uniformity that undermines project efficiency."

Rather than developing entirely new and exclusive Canadian standards for railway electrification, many interviewees emphasized the value of building upon existing international and regional frameworks, particularly those proven through successful implementation.

To accomplish this, a strategic and collaborative approach is recommended, one that first focuses Canadian standardization efforts on contextualizing and complementing existing international standards, rather than trying to build a whole standard ecosystem from scratch. In the meantime, efforts can be made to increase international participation and joint development of standards with international organizations. In each case, Canadian-specific adaptations should result when necessary to account for local climatic conditions, unique regulatory frameworks, and utility interface or inspection practices.

Recommendations

To address the gaps and challenges associated with building on international standards, it is recommended to prioritize the following:

- Adopt the most relevant international standards (IEC 60850 and IEC 62236) with appropriate modifications to address Canada's operational environment, climate conditions, and provincial electrical regulations (i.e., to address the 60 Hz gap); and
- Develop a guide that presents existing international approaches from IEEE and IEC and lists other available standards recommended by CSA Group to fill gaps at the local level. This document must provide practical guidance on how to apply international standards while advising on content gaps that must be considered to reflect Canada's operational environment, including severe winter conditions, provincial electrical regulations, and differences in inspection or utility coordination.

Because the publication of new standards is a consequent process, the following longer-term actions are also recommended:

- Collaborate with the Standards Council of Canada and Canadian industry experts to improve the participation of local experts in the IEC TC 9, Electrical equipment and systems for railways.
- Collaborate in the development of standards with IEEE to address widespread gaps that could be tackled efficiently (the IEEE VTS/TPSSC committee is already addressing specific gaps in the industry, such as DC stray current, system grounding in traction power, etc.).

Active participation in international committees enables collaboration in the development of standards and the integration of Canadian-specific challenges from the beginning, facilitating the confident adoption of such standards. Furthermore, by leveraging the global maturity and credibility of existing standards while tailoring their application to Canadian realities, this approach addresses gaps both upstream and downstream and supports international interoperability and domestic applicability. It prevents unnecessary complexity and cost for manufacturers, while enhancing the consistency and effectiveness of electrification projects across Canada.



4.1.2 Develop National Application Guidelines for Existing Standards

Challenges and Gaps

The research revealed significant inconsistencies in the standards referenced by project developers and applied by designers, even across similar railway electrification projects. This lack of harmonization results in divergent technical approaches with tramway or metro lines built in different regions of Canada. While national standards, such as the CEC and CSA C22.3 NO. 8, are commonly referenced, their scope of application does not align with the specific technical or contextual requirements in the case of light rail electrification projects, for example. As a result, their application can be inadequate and may lead to design inefficiencies or misinterpretations.

In Canadian railway electrification projects, the application of standards often requires a complex selection process due to varying technical contexts and influencing factors, such as project location, procurement strategy, and client familiarity. This highlights the need for clear guidance on which standards to apply and how to ensure their consistent implementation within the Canadian context.

Recommendation

To address these gaps, it is recommended to develop a guide that lists all the relevant technical standards to follow when tendering and developing rail electrification projects, and under what circumstances. It should provide guidance on the application contexts and refer to existing and newer standards that are developed specifically for railway applications. It should also present current standards limits, including clarifying CEC application limits. This guide should include decision trees or tables to help designers and engineers select appropriate standards based on voltage, current type, system architecture, and climate zone.

It is also recommended that this guide is updated frequently or redacted when newer standards (international and local) are adopted or developed by CSA Group.

CSA Group has produced similar guidance for standard users in other fields and on emerging topics [105], [106]. The same approach could be followed for railway electrification, and would help avoid the tendency to “pick and choose” from multiple frameworks, which results in inconsistencies in the industry, design inefficiencies, and interface challenges.

4.1.3 Standards for Dedicated Systems or Applications

Railway electrification encompasses a broad range of technologies and system configurations, each tailored to specific applications, such as LRT, commuter rail, HSR, and freight corridors. However, the current standards landscape in Canada lacks the magnitude and depth required to effectively guide design, implementation, and decision-making across these varied contexts. This section proposes recommendations to address the different gaps encountered through collaboration with external organizations.

4.1.3.1 Traction Power Systems

Challenges and Gaps

The lack of standardization for 25 kV, 60 Hz systems was highlighted in the US by the FRA and the California HSR reports [5], [48], which stress the need for structured guidance in electrification system design tailored to the US context. Although AREMA has provided guidelines, and both IEEE and IEC provide standards on traction power, these documents often fall short of offering concrete criteria for system configuration in the US.

Similar gaps were identified in the Canadian context. Although CSA 22.3 NO. 8 provides an overview of railway electrification, it focuses on AC systems and excludes DC traction power systems. There is also a lack of standards to coordinate all aspects of traction power system design, including voltage selection, substation configuration, and overhead or third rail systems selection. The current Canadian standard landscape simply does not cover all the aspects of these projects. This presents an opportunity to adopt international standards and collaborate internationally and develop key pieces to fill specific gaps.

Recommendations

It is important to develop content to complement the current AREMA guidelines, which are limited in their content and scope, and the IEEE 1653 series on DC up to 1.5 kV. The developed content must consider variables such as evolving climate conditions, terrain, or maintenance requirements. Therefore, it is recommended that CSA Group work collaboratively with the relevant IEEE and IEC committees to consider the Canadian context and develop new standards on the following topics:

- Design of TPSS for DC systems below 3 kV, complementing the voltage gap left by the IEEE 1653 series and CSA 22.3 NO. 8-M91.
- OCS clearances for DC systems below 3 kV for different railway applications and environmental contexts to strengthen harmonization across Canada with provincial and local codes. Clearances can be aligned with Chapter 28 of the AREMA guidelines and CSA Group's previous standards on overhead systems.
- Grounding and bonding of traction power and surrounding components, with a focus on electromagnetic compatibility and stray and induced currents in surrounding infrastructure and in infrastructure corridors. This initiative can be complementary to the IEEE VTS/TPSSC P3175 and 2853 working groups, and can be based on IEC 63438 and IEC 62128.

4.1.3.2 High-Speed Rail

Challenges and Gaps

HSR differs from other AC rail systems with specific technical requirements, such as specialized traction power supply, dedicated overhead contact systems, track infrastructure, advanced communications systems, and clearances to operate at full potential.

The development of HSR in North America faces a particularly acute standards gap. Previous initiatives from AREMA, including a memorandum of understanding with APTA or Chapter 17 of the Manual for Railway Engineering on HSR [107], [108] are considered insufficient by the industry to support the development of US HSR projects. Consequently, HSR projects in California and Texas (defunct) have relied on a blend of imported standards.

CSA 22.3 NO. 8-M91 includes systems using 25 kV and 50 kV at 60 Hz for conventional railway freight or passenger services, but this has been described as too general, and the standard does not openly

address HSR. Furthermore, it also redirects readers to other standards, such as AREMA or IEC, for topics that might not be covered, which illustrates this gap at the local level. Ultimately, CSA 22.3 NO. 8-M91 does not help with selecting an international standard framework to follow that includes HSR specificities.

The patchwork of foreign standards used by designers in local rail projects, together with the absence of extensive local standards, complicates the design, project delivery, and long-term operations for HSR in Canada. This can create confusion among agencies and designers, which could undermine interoperability across regions for a HSR network.

Recommendations

This gap presents an opportunity to improve the current standard landscape for HSR and support Canadian infrastructure projects. It is recommended that the CSA Group develop a framework for HSR systems operating on dedicated rights of way using the following approaches:

- Define a set of proven international standards that Canadian-only HSR projects can systematically rely on. This aligns with the federal government's prioritization of a local HSR corridor. International frameworks encompassing HSR can be used as a basis, such as UIC 70799, IEC 62313, IEC 60494-1, EN 50119, EN 50367, or the EN 15273 series.
- Adopt a strategic approach focused on interoperability by developing a North American 25 kV, 60 Hz framework that includes HSR specifications in collaboration with relevant US institutions (AREMA, IEEE, FRA, APTA), and by developing formal standards and technical criteria for HSR systems tailored to US and Canadian context and applications. This initiative should focus on interoperability of systems with border-crossing potential, based on best practices while addressing the unique operational, environmental, and regulatory conditions.

The resulting standards would provide a reliable and consistent framework for design, procurement, and implementation, reducing project risk and fostering industry confidence in electrification investments. As a result, this should prevent reliance on piecemeal or imported documentation and reduce interoperability and procurement risks.

4.1.3.3 Freight Rail Electrification

Challenges and Gaps

Electrifying freight railways poses distinct challenges, especially for long-distance corridors and electrification on legacy infrastructure. The FRA study, which reviewed existing electrified freight systems and technologies, concluded that the lack of dedicated standards for this application results in uncertainty about technical feasibility and design best practices [5]. Given the range of comparative studies on rail propulsion technologies [22], [71], and the interest among Class I freight operators in decarbonizing their propulsion systems with a focus on battery and hydrogen fuel cell locomotives rather than OCS-only electrification [65], [73], [109], [110], it is essential to consider the full range of technologies in the development of standards.

While CSA 22.3 NO. 8-M91 addresses electrification of conventional railway freight, it is too general and tends to refer to other standards and frameworks that address specific matters for freight rail electrification. Ultimately, CSA 22.3 NO. 8-M91 also leaves a gap when considering other electrification technologies for freight rail.

Because there is interest from the freight rail industry in decarbonizing its locomotives, any standards developed should assist with framing these efforts and standardizing this transition.

Recommendations

Given the landscape and importance of freight rail in Canada and the US, advancing the standardization of electric freight rail applications will require close collaboration with interested parties in the US to develop a coherent and context-sensitive framework. Therefore, it is recommended to develop standards supporting hybrid electrification propulsion technologies, such as those combining OCS and batteries, which address specific technical issues related to freight rail, including:

- OCS clearances with the height of freight cars;
- Compatibility with legacy systems and surrounding infrastructure (rail communication equipment, road infrastructure, power transmission lines, etc.);
- Grounding and bonding;

- Traction power and battery standards; and
- Standards for partial electrification and conversion of existing lines using OCS or 3rd rail.

Establishing a standard approach for consistent and repeatable development of hybrid electrification propulsion technologies will help streamline project development and support current rail decarbonization ambitions of freight rail operators.

4.1.4 Standardization of Operations and Performance

Challenges and Gaps

Another gap identified during the research is the need for coordination and standardized structure across the project lifecycle (design, construction, and maintenance). These tasks are often fragmented across separate firms or teams, leading to inefficiencies, loss of institutional knowledge, and poor integration between design intent and operational reality.

In addition, participants frequently mentioned the need for climate-responsive design criteria tailored to Canadian conditions. Instead of prescribing detailed technical solutions, there is a need for guidance on performance thresholds and environmental durability of systems, such as snow load, freeze–thaw cycles, salinity, icing, and extreme temperature ranges.

Drawing inspiration from the CEN–CENELEC standards, the Köppen climate classification system could be used to develop a Canadian framework that provides methods to categorize and address regional climate conditions, offering a more nuanced approach than the current general references to "cold climate." Participants emphasized the importance of including climate change adaptation in any future standardization efforts. As extreme weather events become more frequent, systems will need to account not only for historical data but also for projected future variability. Agencies should be encouraged to define acceptable operational thresholds (e.g., fault tolerance during extreme weather, corrosion resistance over decades) and incorporate resilience planning into design and procurement processes with the proper tools.

To improve project outcomes and long-term reliability, there is a growing consensus that standardization efforts should be structured around performance- and operations-based design outcomes (e.g., defining and using reliability criteria, uptime target, safety thresholds, and environmental durability targets that will influence design decision), complementing the technical standards for system components. Such an approach acknowledges the diversity of railway applications across Canada and allows for flexibility in technology selection while ensuring alignment with critical performance, safety, and environmental objectives.

Recommendations

To address these gaps, it is recommended to develop a standardized approach to RAMS studies, using a systems-based approach, for Canadian railway electrification. This is essential to ensure consistent, high-performance system design. This standard should offer comprehensive guidance on integrating key project variables, including:

- Regional climate conditions (using a climate classification framework and accounting for climate change);
- Interactions with surrounding rail and utilities infrastructure;
- Mixed-use corridor considerations; and
- Expected operational performance.

To support practical application, the standard should include tools such as component interaction maps, performance benchmarks from existing systems, and examples of lifecycle and reliability targets. By promoting a systems-based methodology, this standard will enable designers and transit agencies to align technical decisions with operational requirements and environmental realities, fostering more resilient, efficient, and context-sensitive electrification projects.

Ultimately, it will encourage the early involvement of operations and maintenance personnel in design discussions, fostering continuity and accountability throughout the system lifecycle. Previous efforts for standardizing risk evaluations have been made with CSA R114, but a systemic



"The economics of railway electrification remain a central concern, particularly in freight rail applications, where the return on investment must be carefully weighed against high upfront capital costs and uncertain long-term benefits."

approach considering all phases should be included as well. EN 50126 and the IEC 62278 series can be used as the basis for a local standard.

Providing these tools for operational definition and planning will allow transport agencies to define their operational needs and performance outcomes up front, using structured guidance. The resulting clear operational definitions will lead to better delivery strategies, reduced lifecycle costs, and enhanced reliability, and it will foster more consistent delivery of rail electrification projects across Canada. Without this clarity, agencies risk over-customizing projects, inflating costs, or compromising future operations and adaptability.

4.1.5 Economics of Railway Electrification Projects

Challenges and Gaps

The economics of railway electrification remain a central concern, particularly in freight rail applications, where the return on investment must be carefully weighed against high upfront capital costs and uncertain long-term benefits.

In the freight rail sector, major operators such as CN and CPKC, which together own over 70% of Canada's rail infrastructure, have historically questioned the business case for electrification [7]. The Association of American Railroads has emphasized the already high energy efficiency and low GHG emissions intensity of freight rail on a per-tonne-kilometre basis, arguing that the marginal gains from electrification may not justify the extensive infrastructure investments that would be required [5]. Because the electrification of freight corridors would be privately funded, the economic case must rest on clear, quantifiable benefits, including cost certainty, energy pricing stability, and predictable long-term returns. Any shift toward electrified freight operations would also require a re-evaluation of existing business models, fleet strategies, and network-wide operations.

In the context of commuter and intercity rails, the economic rationale often incorporates broader public value considerations [75], [111]. These projects are typically led by public organizations and justified based on a combination of direct transportation and environmental outcomes and indirect social equity benefits, such as the improvement of transport service level, urban development response, or enhanced service reliability and access. While the electrification of intercity rail systems has been the subject of recurring studies since the mid-20th century, cost remains a persistent barrier to implementation, particularly for systems with lower ridership or more diffuse infrastructure needs [76]. This challenge is equally present in light rail and streetcar systems, where cost overruns, project complexity, and localized constraints often drive project delays or redesigns [51], [79], [80], [81].

Although political priorities and capital funding decisions of corporations fall outside the scope of standardization, there is a strong case for improving the transparency and comparability of project economics through standardized approaches.

Recommendations

It is recommended to develop a standard that establishes a unified framework for presenting project costs and performance indicators for railway electrification projects. This standard should encompass presentation of project cost categories, including capital expenditures, land acquisition, engineering and installation costs, with configuration-specific cost breakdowns (e.g., for OCS, battery-electric, or hydrogen systems). It will support consistent and transparent evaluation of railway electrification projects through standardized presentation formats that incorporate key performance indicators reflecting the full range of project benefits. These indicators can include:

- Standardized cost metrics, such as cost of development per kilometre, enabling cross-project comparisons and benchmarking;
- Environmental performance, including GHG emissions reduction, air quality improvements, and land use efficiency;
- Accessibility outcomes, such as improved mobility for underserved populations and integration with other transit modes;
- Territorial economic impact, capturing job creation, regional development, and supply chain stimulation; and
- Energy efficiency, including system-level energy consumption and grid integration performance.

By embedding these indicators into project documentation, agencies and other interested parties can better assess value, support harmonized decision-making, and communicate benefits to the public and funding bodies. Considering the growing diversity of decarbonization pathways for transport and rail, such guidance is critical for aligning technology adoption with project-specific goals and constraints.

Improving economic clarity through standardized practices will not eliminate all barriers, but it can help level the playing field in the transport and rail industry, making projects more comparable, defensible, and transparent. This is essential both for enabling public investment and for supporting private sector buy-in, particularly in freight applications, where operations profitability is a primary driver.

4.1.6 Guidelines for the Inspection of Railway Power Installations

Challenges and Gaps

The successful delivery of railway electrification projects depends not only on proper design and construction but also on robust inspection procedures that confirm installations meet operational requirements and safety standards prior to commissioning.

Current inspection frameworks, mainly provided by APTA, are limited to transit systems and do not address the inspection of long-distance rail or HSR or the delivery of newly built systems. Across Canada, experiences have highlighted the importance of inspections, particularly when it comes to verifying compliance with applicable codes and assessing whether installations align with the intended operations. There is a harmonization gap in installation quality and lifecycle performance between provinces that needs to be addressed.

Recommendations

Drawing on the learnings and insights shared during interviews, it is recommended to establish a nationally standardized inspection framework specific to railway power installations. This framework will address the current lack of uniform inspection practices across different jurisdictions and rail system types by:

- Addressing the handover procedure of systems with verification of potential flaws that might cause failures in real-world operating conditions;
- Assessing key components such as load capacity, fault tolerance, and grounding integrity, as well as resilience to climatic conditions, including icing, snow accumulation, and mechanical stress on OCS;

- Including pre-commissioning checklists tailored to specific system types, such as light rail, commuter rail, HSR, and freight operations;
- Clearly defining roles and responsibilities during inspection phases to ensure accountability and proper coordination among all involved parties, including contractors, engineers, inspectors, and operators;
- Incorporating standardized documentation tools, such as reporting templates and punch list management procedures, which will ensure transparency and facilitate tracking of inspection outcomes; and
- Providing inspection timelines, which can be aligned with construction milestones and commissioning plans to ensure inspections are integrated seamlessly into project schedules.

These guidelines should be developed according to the following two core purposes:

1. The framework should support local authorities (particularly provincial, municipal, and utility inspectors) by providing a structured reference that enables consistent application of inspection protocols regardless of the region. This is especially important considering the evolving nature of traction power systems, which do not always fit neatly into traditional inspection categories.
2. The framework should ensure operational readiness. Each installation must be confirmed as fit for service under its specific design and environmental conditions.

Standardizing the inspection process in this way will not only improve quality assurance across electrification projects but will also empower transit agencies and developers to make well-informed decisions at the project handoff stage. Ultimately, it will help ensure that installations are safe, complete, and operationally viable, reinforcing public confidence, protecting worker safety, and enhancing the long-term performance of Canada's electrified rail systems.

4.1.7 Standards for the Maintenance of Traction Power Installations

Challenges and Gaps

As Canada's rail electrification infrastructure develops, the importance of standardized, safety-oriented maintenance practices becomes increasingly critical. Across the country, operators of legacy networks, including Class I freight railroads, LRT systems, and commuter rail agencies, follow maintenance procedures that have evolved through decades of operational experience. These practices are often based on in-house documentation and informal knowledge transfer between individuals, shaped around the equipment and configurations specific to each system.

While many rail agencies anchor their procedures in general safety frameworks, such as NFPA, CSA Group, and IEEE standards for electrical safety and current exposure thresholds, a notable gap remains in dedicated guidance for the maintenance of traction power systems, including OCS, TPSS, grounding networks, and associated control systems that present distinct hazards not always fully addressed in general electrical codes.

Several gaps were identified during the research, including the lack of maintenance guidelines for rail-specific DC power transmission and distribution compared to AC powered installations. Challenges were also identified with the exposure to arc flash conditions during the maintenance of DC TPSS, as there is no standard that addresses this topic with a calculation methodology.

Another issue that was observed is the wide variability in maintenance practices between agencies. In the absence of a common standard, inspection intervals, safety protocols, and failure response procedures can differ significantly, leading to inconsistent performance outcomes and potential operational inefficiencies. This disparity becomes even more problematic in aging systems, where preventive maintenance and structured diagnostics are essential to avoid system failures.

Furthermore, legacy maintenance procedures are not well documented. Much of the institutional knowledge

resides informally within long-serving staff, which makes it difficult to ensure consistent training for new personnel with standard training material. This contributes to skill gaps and complicates workforce transitions. At the same time, modern standards for safety arc flash protection, stray current mitigation, and energy isolation, such as those outlined in CSA Z462, do not apply to rail installations and are not consistently applied, particularly in older networks that were built before the adoption of these codes.

Recommendations

To address these gaps, it is recommended to develop two standards outlining maintenance procedures through inspection requirements and minimum safety requirements for both DC and AC traction systems, ensuring alignment with existing CSA Group, APTA, and IEEE frameworks while filling in areas specific to rail electrification. Specifically, it is recommended to:

- Develop a standard for the maintenance of railway electrical traction power systems, either through creation of a new standard or by expanding CSA Z463. The standard should outline procedures for routine, preventive, and corrective maintenance of key components, including OCS, TPSS, switchgear, grounding systems, and bonding infrastructure. These procedures can be informed by existing maintenance practices used in electrical grid systems, while accounting for the specific requirements of electrified rail systems, such as OCS, third rail, and transformer rectifier units. Importantly, the standard should recommend risk-based inspection schedules that account for variables such as asset age, duty cycle, load conditions, and environmental exposure.
- Develop a standard for work safety practices for traction power systems, either through creation of a new standard or by improving CSA Z462. This standard should address gaps in risk analysis, safe work procedures, protective equipment, and arc flash hazards in both AC and DC traction power environments.

By formalizing these practices into unified, nationally recognized standards, Canada's rail sector can move away from reliance on informal procedures and ensure consistent, safe, and cost-effective maintenance across jurisdictions. This would not only strengthen safety outcomes and extend asset lifespans but also lay the groundwork for smoother integration of future upgrades and emerging technologies.

Supporting workforce development is also essential. Both recommended standards should highlight training and skill frameworks to ensure maintenance personnel are qualified to work in energized rail environments. The development of these standards should stimulate discussion and collaboration between transit agencies, work safety organizations, utilities, and contractors, enabling the exchange of best practices and improving readiness for retrofits or system expansions.

4.1.8 Training and Accreditation for Electrified Railway Systems

Challenges and Gaps

A recurring theme in both the literature review and the industry engagement was the critical shortage of locally trained and specialized labour in the field of railway electrification. As more transit agencies and rail operators pursue electrification projects, the demand for qualified personnel, particularly for roles involving traction power systems, installation, and inspection, has outpaced the availability of workers with the necessary technical expertise and field experience. While APTA has published documents to support the skills and procedures for transit agency workers, third parties and external contractors must be trained and recognized as well.

Many interview participants, especially those engaged in project delivery and field installation, emphasized that OCS installation is a highly specialized trade that requires not only familiarity with high-voltage electrical systems but also a deep understanding of alignment, tensioning techniques, safety protocols, and environmental adaptation. Several organizations reported that, due to the absence of formal training programs in Canada, they have had to rely on on-the-job learning, international subcontractors, or extended ramp-up periods for new personnel. This lack of training has introduced avoidable risks and delays into project timelines.



The shortage of specialized training programs for the design and installation of electrified railway systems is compounded by a lack of formal recognition for professionals in this field. Without standardized curricula or certification pathways, newly trained personnel face uncertainty regarding their qualifications and career progression. This gap not only undermines workforce development but also poses risks to project quality and safety, as there is no consistent benchmark to validate skills or ensure competency across jurisdictions.

Recommendations

To address these challenges, it is recommended to develop nationally standardized training and certification programs tailored to the needs of railway electrification, including:

- A standard for technical training programs dedicated to tradespeople involved in OCS installation, substation commissioning, and traction system maintenance, which will ensure consistency of skills and techniques in the workforce and help reduce project quality risk factors; and
- A certification pathway for personnel responsible for high voltage safety verifications, field inspections, and system commissioning activities in electrified railway contexts.

To support project-level quality assurance, a contractor accreditation system could also be implemented. This would help identify and recognize firms with a proven ability to deliver safe, compliant, and high-quality electrified infrastructure, thereby reducing project risk and encouraging procurement practices that prioritize performance.

The Standards Council of Canada has already launched initiatives to certify safety conformity assessors and evaluators working in the rail sector [112]. Building on this momentum, certification programs could be developed to include personnel and organizations involved in the design and construction of electrified railway projects, which would help establish a nationally recognized baseline for worker qualifications and safety practices while also enhancing overall consistency and performance across Canadian railway projects.

Establishing standardized requirements for training and certification programs can reduce the variability in installation quality currently observed between different regions and agencies. It would also lead to better safety outcomes for workers and transit system users, while supporting both public agencies and contractors in meeting future CSA Group standards and guidelines. Moreover, the development of structured training and accreditation pathways would help create long-term career opportunities, increasing workforce stability and resilience in what is rapidly becoming a core segment of Canada's clean transportation sector.

In this context, workforce development is more than just a response to current labour shortages, it is a foundational pillar for ensuring the success and safety of railway electrification in Canada. As the country pursues ambitious decarbonization goals and modernizes its transport infrastructure, the availability of a consistent, skilled, and certified workforce will be essential to build and maintain this infrastructure. Embedding training and certification within the broader framework of technical standards will not only reduce risk and improve reliability but also reinforce public confidence and support the domestic capacity needed to deliver resilient and interoperable electrified rail systems. In doing so, Canada can position itself as a leader in the delivery of safe, efficient, and future-ready railway electrification.

4.1.9 Summary of Standardization Gaps and Recommendations

Section 4.1 discussed gaps and challenges around railway electrification in Canada that were identified during the research, and presented recommendations and opportunities for standardization across key areas. Table 6 provides a summary of traction power component gaps and systemic gaps, along with recommended solutions to address them.

Table 6: Summary of Standardization Gaps and Recommendations

Area	Gaps	Recommendations
Power Transmission and Distribution	Use of CEC for the design of traction power applications despite its inapplicability in rail installations, which may lead to design inefficiencies or misinterpretations.	▪ Develop a guide that lists all the relevant standards to follow when developing rail electrification projects, and under what circumstances, clarifying the scope of the CEC in rail projects and when the limits apply.
	Lack of rail power supply definitions for 60 Hz grid conditions.	▪ Adopt the most relevant international standards (IEC 60850 and IEC 62236) with modifications addressing the 60 Hz issue. ▪ Promote Canadian expert participation in international standardization work by committees such as IEC TC 9 to consider Canadian-specific conditions (i.e., 60 Hz) in newer IEC publications.
	Lack of maintenance guidelines for DC traction power transmission and distribution.	▪ Develop a standard for the maintenance of traction power systems, including DC-specific conditions encountered in electrified railways, either by expanding CSA Z463 or by creating a new standard.

Area	Gaps	Recommendations
Traction Power Substations	Inapplicability of the CEC and lack of Canadian guidance for rail traction power substations design.	▪ Adopt the relevant international traction power transmission and distribution standards with necessary modifications. ▪ Develop a guide highlighting which standards to follow, their scope of application, and explicit limits of the CEC in the front of the metre context (railway station vs. traction power). Look to other CSA Group guides on innovative topics with new standards (water, electric vehicles).
	Lack of dedicated standard for TPSS design, especially in DC systems below 3 kV.	▪ Develop a standard for DC TPSS design below 3 kV, ▪ Collaborate with the IEEE VTS/TPSSC to develop standards and address the widespread gaps in traction power substations.
	Lack of harmonized grounding and bonding standard for DC TPSS.	▪ Develop standards for the grounding and bonding of traction power and surrounding components, with a special focus on DC traction. ▪ Collaborate with the IEEE VTS/TPSSC already working on grounding and bonding for DC TPSS.
	Challenges with installation and maintenance in DC arc flash TPSS situations.	▪ Standardize work safety and maintenance practices for traction power systems, especially in DC power, through new standards or by expanding CSA Z462 and CSA Z463.
Overhead Catenary Systems	Incomplete design standards across the range of rail electrification voltages and current types.	▪ Develop a standard on OCS clearances under 3 kV in DC for different railway applications and environmental contexts to improve harmonization across the country.
	Climate and environmental adaptation gaps in current standards.	▪ Adopt the most relevant international standards (e.g., IEC 60913) with modification to address Canadian regional climate conditions. ▪ In future standards, incorporate evolving climate conditions into design criteria to ensure system reliability over the coming decades.
	Insufficient guidance on inspection, maintenance, and safety procedures.	▪ Develop a standardized inspection method and framework for railway installations encompassing OCS. ▪ Develop a standard for the safe maintenance of OCS, through new standards or by expanding CSA Z463 and CSA Z462.
	Limited standardized local training and specialized tools for OCS installation.	▪ Standardize training requirements and certification programs in the electrified railway field, including the installation and maintenance of OCS.

Area	Gaps	Recommendations
Grounding and Bonding	Lack of design standards for grounding and bonding, including induced current, surge and fault protection, and electromagnetic compatibility management in infrastructure corridors.	▪ Collaborate with IEEE to develop standards for the grounding and bonding of traction power and surrounding components. Collaboration with the IEEE VTS/TPSSC P3175 and 2853 working groups is particularly relevant to address this gap. ▪ Develop a standardized inspection method and framework for railway installations, addressing grounding and bonding systems.
	Lack of standards for voltage limiting devices, surge protection, and insulation coordination for DC systems.	▪ Develop standards for the grounding and bonding of traction power and surrounding components, with a special focus on DC traction.
Systemic Gaps	Lack of accountability (company and individual) in design.	▪ Adoption of international standards, with or without modifications, and development of new standards will improve standard practices and reduce the lack of accountability for both companies and individuals. ▪ Standardize training requirements and build skill recognition pathways (certifications) for electrified railway designers.
	Lack of cost evaluation presentation and cost modelling standard.	▪ Develop a standard for project costs and performance presentation, including indicators of costs and benefits.
	Lack of harmonized rail installation inspection and maintenance framework.	▪ Develop a standardized inspection method and framework for railway installations to harmonize practices and installation quality. ▪ Develop a standard for the maintenance of traction power systems. This could be achieved by expanding CSA Z463 or by creating a new standard.
	Lack of specialized labour training for electrified railways.	▪ Standardize training requirements and certification programs in the electrified railway field. This recommendation applies to the workforce involved in the design and installation of systems.
	Need for international collaboration in the development of new standards and publications.	▪ Promote Canadian expert participation in international standardization work underway by committees such as IEC TC 9. ▪ Collaborate with the IEEE VTS/TPSSC to address widespread gaps that can be tackled efficiently.
	Lack of design guidance for projects using mixed-use rail infrastructure and with surrounding utilities infrastructure interactions.	▪ Develop a standard approach to the RAMS studies for railway electrification encompassing legacy rail and surrounding infrastructure interactions such as nearby rail or power infrastructure. EN 50126 and the IEC 62278 series can be used for inspiration.
	Need for a HSR standard framework.	▪ Define a set of proven international standards that Canadian-only HSR projects can rely on (e.g., UIC 707 series, IEC 62313, IEC 60494-1, EN 50119, EN 50367 or EN 15273). ▪ Develop a collaborative framework with relevant US institutions (AREMA, IEEE, FRA, APTA) aimed at North American HSR interoperability.
	Lack of a freight electrification standard framework to support current decarbonation initiatives.	▪ Develop a standard based on needs and current initiatives, considering hybrid technologies with OCS and battery, and aligned with specifics of freight rail operations.

4.2 Recommendations for Future Research

To help ensure that future railway electrification standards are grounded in practical evidence and reflective of Canadian realities, targeted research is essential. These types of focused studies can address critical knowledge gaps, validate design assumptions, and inform the development of adaptable, performance-based standards. From climate resilience and lifecycle costing to safety protocols and interoperability, a series of topics for further research is recommended below to support the ongoing evolution of codes, guidelines, and implementation practices.

4.2.1 Technical Systems and Infrastructure

Findings from the research showed that several technical topics linked to components or environmental factors need to be further investigated to understand the potential gaps in the rail electrification standardization landscape, including:

- **Rolling Stock, Communication and Signals:** This report excluded rolling stock and signalling and communications from its scope. Although CSA 22.3 NO. 8 addresses this topic, future research should explore the standardization gaps on these two components in railway electrification.
- **Climate-Adapted Design Criteria:** CSA Group is currently conducting research on the impact of climate change on rail and public transit systems. The results of such research must inform the design consideration in order to address climate change scenarios, and temperature and precipitation impact occurrence, and to consider different climate regions across the country, as well as the projected lifecycle and location of rail systems.
- **Corrosion and Stray Current Mitigation:** Future research should compare protection systems across soil types, salinity, and configurations; assess long-term grounding performance.
- **Electrification Impacts:** Future research should study interactions between rail systems and utility grids, focusing on electromagnetic compatibility, fault currents, regenerative braking, and power quality under decarbonized grids.
- **Component Interface Standardization:** Future research should continue to examine freight electrification with alternative technologies, such as hybrid OCS-battery, diesel-OCS, and diesel locomotive retrofitting. Review mechanical and electrical interface variations in OCS, TPSS, and SCADA to enable plug-and-play integration and multi-vendor compatibility.

4.2.2 Standards and Certification

- **Domestic Manufacturing Support:** Future research should identify gaps in Canada's production capacity and propose adaptation standards and low-carbon certification pathways.

4.2.3 Digitalization and Maintenance

Discussions with several interested parties also raised two specific topics in the digital field that should be included in future research:

- **AI and Predictive Maintenance:** Future research should investigate AI applications for inspection scheduling, diagnostics, and asset tracking. It should also define data infrastructure needs.
- **Cybersecurity:** Future research should prioritize cybersecurity standardization to provide a framework for the protection of remote monitoring and control systems for power infrastructure, ensuring resilience against digital threats and unauthorized access.

5 Conclusions

Railway electrification and decarbonization projects are gaining momentum across North America, aiming to strengthen local and regional transport networks. Given Canada's ambitious GHG emissions reduction targets, rail is increasingly viewed as a cornerstone of low-carbon transportation. However, several barriers continue to hinder the development of these projects.

Through a literature review of industry publications and engagement with interested parties, the research conducted for this report identified key technical and systemic gaps in the Canadian and US standards landscape for railway electrification. The findings indicate that current Canadian technical standards

do not fully address the diverse conditions under which traction power components operate, nor do they adequately cover certain rail applications, such as HSR. In practice, these gaps are often filled for each project using a patchwork of international standards (e.g., IEC, IEEE, CEN–CENELEC) and locally developed guidance (e.g., provincial codes, utility codes, project guidelines), but this strategy has been criticized for its lack of repeatability and its negative impact on project development timelines and costs.

Systemic gaps related to broader organizational and procedural issues were also identified and included the need for improved inspection and maintenance protocols, better coordination among interested parties, clearer guidance on environmental conditions and performance definitions, and standardized project evaluation frameworks. These systemic issues, while challenging, also present a strategic opportunity for standardization.

The recommendations outlined in this report are designed to support the effective rollout of railway electrification projects in Canada by bridging critical gaps in both local and international standardization. By addressing challenges across the full project lifecycle, from planning and design to operation and maintenance, these recommendations aim to improve consistency, enhance safety, and streamline project implementation. The recommended standards seek to reduce complexity, promote interoperability, and enable cost-effective, future-ready infrastructure, aligning with global best practices and existing standard innovations. Ultimately, this approach lays the groundwork for a cohesive and resilient national framework that can accelerate Canada's transition to sustainable electric rail systems.

References

[1] B. E. Sullivan. "Street railways." The Canadian Encyclopedia. Accessed: Dec. 26, 2024. [Online]. Available: https://www.thecanadianencyclopedia.ca/en/article/street-railways

[2] J. Young. "Locomotives and rolling stock." The Canadian Encyclopedia. Accessed: Feb. 2025. [Online]. Available: https://www.thecanadianencyclopedia.ca/en/article/locomotives-and-rolling-stock

[3] Railway Association of Canada, "Rail trends 2023," Railway Association of Canada, Ottawa, ON, Canada, Dec. 2023. [Online]. Available: https://www.railcan.ca/wp-content/uploads/2023/12/EN-FINAL-RAC-RAIL-TRENDS-2023.pdf

[4] A. Regenstreif, "Developing higher speed electric railways across Canada," Transport Action Ontario, Toronto, ON, Canada, Jun. 2015. [Online]. Available: https://ontario.transportaction.ca/wp-content/uploads/2015/06/TAO-HSR-Paper-Final2015-06.pdf

[5] C. T. Dick, R. D. Walthall, M. E. Iden, and J. R. Blaze, "Cost and benefit risk framework for modern railway electrification options," Federal Railroad Administration, United States Department of Transportation, Washington, DC, United States, Jan. 2025. [Online]. Available: https://railroads.fra.dot.gov/sites/fra.dot.gov/files/2025-01/CB%20Framework%20Rail%20Electrification%20Options.pdf

[6] Railway Association of Canada, "A parliamentarian's guide to Canada's railways," Railway Association of Canada, Ottawa, ON, Canada, Jan. 2016. [Online]. Available: https://www.railcan.ca/wp-content/uploads/2023/02/A-Parliamentarians-Guide-to-Canadas-Railways.pdf

[7] Transport Canada, "Transportation in Canada 2023," Transport Canada, Ottawa, ON, Canada, 2024. [Online]. Available: https://tc.canada.ca/sites/default/files/2024-06/TC_2023_Annual_Report_EN_2024-05-29.pdf

[8] Transport Canada. "Transportation in Canada 2021: Greenhouse gas emissions." Accessed: Apr. 11, 2025. [Online]. Available: https://tc.canada.ca/en/corporate-services/transparency/corporate-management-reporting/transportation-canada-annual-reports/2021/greenhouse-gas-emissions

[9] Rail Baltica, "Design guidelines: Railway control-command signalling system," Rail Baltica, Riga, Latvia, Jul. 31, 2023. [Online]. Available: https://www.railbaltica.org/wp-content/uploads/2025/09/RBDG-MAN-022-0103_RailwayControlCommandSignallingSystem.pdf

[10] T. Gerbet, L. Blouin, and M. Prost. "Federal government going ahead with high-speed rail between Quebec City and Toronto." CBC. Accessed: Jan. 2025. [Online]. Available: https://www.cbc.ca/news/politics/high-speed-rail-canada-1.7365835

[11] Alto. "Discover the project's features and many benefits." Accessed: Apr. 11, 2025. [Online]. Available: https://altotrain.ca/en/discover-the-projects-features-and-many-benefits

[12] Metrolinx. "GO Rail network electrification." Accessed: Jan. 2025. [Online]. Available: https://www.metrolinx.com/en/projects-and-programs/go-expansion-studies/go-electrification

[13] H. Ould-Hammou and R. Watts. “Quebec unveils new details about future Quebec City tramway.” CBC. [Online]. Available: https://www.cbc.ca/news/canada/montreal/quebec-city-tramway-update-1.7411451

[14] City of Mississauga. “Hurontario Light Rail Transit.” Accessed: Apr. 15, 2025. [Online]. Available: https://www.mississauga.ca/projects-and-strategies/city-projects/hurontario-light-rail-transit

[15] C. Reynolds. “Delays, Trudeau resignation threaten Toronto–Quebec City high-frequency rail project.” Global News. Accessed: Jan. 28, 2025. [Online]. Available: https://globalnews.ca/news/10954955/delays-trudeau-resignation-threaten-toronto-quebec-city-high-frequency-rail-project

[16] O. Lemieux and L. Gagné. “Quebec trying to secure federal funding for tramway before the election.” CBC. Accessed: Jan. 28, 2025. [Online]. Available: https://www.cbc.ca/news/canada/montreal/quebec-tramway-project-federal-government-funding-1.7438565

[17] D. Olive. “Runaway rail dreams. Why Ottawa’s high-speed plan for Toronto–Quebec corridor is unlikely to reach its destination.” The Toronto Star. [Online]. Available: https://www.thestar.com/business/runaway-rail-dreams-why-ottawas-high-speed-plan-for-toronto-quebec-corridor-is-unlikely-to/article_90664648-9dff-11ef-862b-57a70753fe71.html

[18] Transport Action Canada. “Cadence wins $3.9B High Speed Rail development contract but delivery timeline is cause for concern.” Accessed: Apr. 15, 2025. [Online]. Available: https://www.transportaction.ca/topics/intercity-rail-and-bus/cadence-wins-3-9b-high-speed-rail-development-contract

[19] Effective Transit Alliance. “The right route to rail decarbonization is electrification.”Accessed: Feb. 2025]. [Online]. Available: https://www.etany.org/rail-electrification

[20] E. Chung, “Why Canada is so far behind Europe in electrifying rail.” CBC. [Online]. Available: https://www.cbc.ca/news/science/what-on-earth-canada-trains-europe-electric-1.6450892

[21] C. Anderson *et al.,* “Sierra Club rail transportation statement,” Sierra Club, Oakland, CA, United States, Aug. 2023. [Online]. Available: https://www.sierraclub.org/sites/default/files/2023-08/Rail%20Report%20FINAL.pdf

[22] The Delphi Group and Pollution Probe, "Towards Net Zero: Developing a Rail Decarbonization Roadmap for Canada," 2022. [Online]. Available: https://www.railcan.ca/wp-content/uploads/2022/12/Rail-Pathways-Decarbonization-Roadmap.pdf

[23] Rail Baltica, “Design guidelines: Railway energy, Part 1: Traction power system,” Rail Baltica, Riga, Latvia, May 6, 2025. [Online]. Available: https://www.railbaltica.org/wp-content/uploads/2025/09/RBDG-MAN-018-0103_DG_RailwayEnergyPart1-TractionPowerSystem.pdf

[24] Swartz Engineering. “Railway power systems and overhead lines.” Accessed: Aug. 2025. [Online]. Available: https://www.swartzengineering.com/blog/railway-power-systems-and-overhead-lines

[25] International Union of Railways. “The definition of high speed rail.” [Online]. Available: https://www.uic.org/com/enews/nr/596-high-speed/article/the-definition-of-high-speed-rail?page=thickbox_enews

[26] A. Schlunk and M. Shurland, "Proceedings of FRA workshop on environmentally sustainable energy technologies powering future of rail," Federal Railroad Administration, United States Department of Transportation, Washington, DC, United States, Feb. 2022. [Online]. Available: https://railroads.dot.gov/sites/fra.dot.gov/files/2022-02/FRA%20Future%20of%20Rail%20Workshop.pdf

[27] Mexico Business News. "Mexico to invest MX$157 billion in railway projects." Accessed: Jan. 2025. [Online]. Available: https://mexicobusiness.news/infrastructure/news/mexico-invest-mx157-billion-railway-projects-0

[28] J. G. Allen, "Reasons for commuter rail electrification: Early 20th century and since 2000," Transp. Res. Rec.: *Journal of the Transportation Research Board,* vol. 2673, no. 7, pp. 227–238, 2019, https://doi.org/10.1177/0361198119840621.

[29] International Trade Administration. "Mexico fast-tracks new rail infrastructure projects." Accessed: Aug. 7, 2025. [Online]. Available: https://www.trade.gov/market-intelligence/mexico-new-rail-infrastructure-projects

[30] Caltrain. "Program overview." Accessed Apr. 15, 2025. [Online]. Available: https://www.caltrain.com/projects/electrification

[31] FreightWaves.com. "California gives up on zero-emissions locomotive regulation." Accessed: Jan. 22, 2025. [Online]. Available: https://www.freightwaves.com/news/california-gives-up-on-zero-emissions-locomotive-regulation

[32] Alstom. "First in the Americas: Alstom's hydrogen train enters revenue service in Charlevoix in Quebec." Accessed: Jan. 2025. [Online]. Available: https://www.alstom.com/press-releases-news/2023/6/first-americas-alstoms-hydrogen-train-enters-revenue-service-charlevoix-quebec

[33] Mass Transit. "First hydrogen-powered FLIRT H2 passenger train arrives at San Bernardino Depot Train Station." Accessed: Jan. 2025. [Online]. Available: https://www.masstransitmag.com/rail/vehicles/press-release/55090971/san-bernardino-county-transportation-authority-sbcta-first-hydrogen-powered-flirt-h2-passenger-train-arrives-at-san-bernardino-depot-train-station

[34] P. Zimonjic, M. Prost, and S. Bordeleau. "High-speed rail line with 300 km/h trains will run between Toronto and Quebec City, Trudeau announces." CBC. Accessed: Feb. 19, 2025. [Online]. Available: https://www.cbc.ca/news/politics/trudeau-announces-high-speed-rail-quebec-toronto-1.7462538

[35] Transport Canada. "2023–2030 memorandum of understanding between Transport Canada and the Railway Association of Canada for reducing locomotive emissions." Accessed: Feb. 24, 2025. [Online]. Available: https://tc.canada.ca/en/corporate-services/policies/2023-2030-memorandum-understanding-between-transport-canada-railway-association-canada-reducing-locomotive-emissions

[36] Government of Alberta. "Passenger rail." Accessed: Feb. 19, 2025 [Online]. Available: https://www.alberta.ca/passenger-rail

[37] Réseau express métropolitain. "The REM under construction: Work schedule." [Online]. Available: https://rem.info/en/under-construction/work-schedule

[38] Metrolinx. "GO Expansion." Accessed: Feb. 2025. [Online]. Available: https://www.metrolinx.com/en/projects-and-programs/go-expansion

[39] TransLink. "Millennium Line UBC extension." Accessed: Feb. 21, 2025. [Online]. Available: https://www.translink.ca/plans-and-projects/projects/rapid-transit-projects/millennium-line-ubc-extension

[40] Surrey Langley Skytrain. "Project overview: The Surrey Langley Skytrain project will extend the Expo Line 16 kilometres." Accessed: Feb. 2025. [Online]. Available: https://surreylangleyskytrain.gov.bc.ca/project-overview

[41] City of Hamilton. "Plans and strategies: Light Rail Transit (LRT)." Accessed: Feb. 21, 2025 [Online]. Available: https://www.hamilton.ca/city-council/plans-strategies/light-rail-transit-lrt

[42] Ville de Québec. "Le tramway de Québec." Accessed: Feb. 21, 2025 [Online]. Available: https://www.ville.quebec.qc.ca/apropos/planification-orientations/transport/tramway/index.aspx

[43] N. Quellec, S. Aboukircha, and P. Kerhoas, "Rapport sur le choix du système de captage de traction," Co-entreprise AECOM SYSTRA and Caisse de dépôt et placement du Québec, Montreal, QC, Canada, 2021. [Online]. Available: https://www.cdpqinfra.com/sites/cdpqinfrad8/files/2022-03/Rapport-alimentation-electrique_REMEST_2021.pdf

[44] Metrolinx. "Building a strong foundation for GO Expansion's OnCorr project." Accessed: Jan. 2025 [Online]. Available: https://www.metrolinx.com/en/discover/building-a-strong-foundation-for-go-expansion-oncorr-project

[45] *Capital Projects Group Performance Specifications for Electric Traction Enabling Works,* MX-ELEC TRAC EW-SPEC-2016, Metrolinx, Toronto, ON, Canada, 2018. [Online]. Available: https://assets.metrolinx.com/image/upload/v1737998921/Documents/Engineering/CPG_Performance_Specifications_for_ET_EW.pdf

[46] *Go Electrification Enabling Works ET Standards,* MX-ELEC-TRAC EW-DW-2016-REV1, Metrolinx, Toronto, ON, Canada, 2016. [Online]. Available: https://assets.metrolinx.com/image/upload/v1737993006/Documents/Engineering/Enabling_Works_ET_Standard_MX-ELEC_TRACT_EW-DW-2016-REV1.pdf

[47] *High Floor LRT Design Guidelines,* Version 02, COE-IM-GUIDE-0017, City of Edmonton, Edmonton, AB, Canada, 2022. [Online]. Available: https://www.edmonton.ca/sites/default/files/public-files/assets/LRTDesignGuidelines.pdf

[48] California High-Speed Rail Authority, "California High-Speed Train Project: System requirements database report," California High-Speed Rail Authority, Sacramento, CA, United States, 2010. [Online]. Available: https://calhsr.com/wp-content/uploads/2010/08/rpt_CHSTP_System_Requirements_Full_Details.pdf

[49] Rail Baltica, "Design guidelines: Railway telecommunications system," Rail Baltica, Riga, Latvia, Aug. 31, 2023. [Online]. Available: https://www.railbaltica.org/wp-content/uploads/2025/07/RBDG-MAN-023-0102_RailwayTelecommunicationsSystem.pdf

[50] Rail Baltica, "Design guidelines: Railway energy, Part 2: Overhead contact line system," Sep. 6, 2025. [Online]. Available: https://www.railbaltica.org/wp-content/uploads/2025/09/RBDG-MAN-019-0104_DG_RailwayEnergyPart2-OverheadContactLineSystem.pdf

[51] J. Mok, M. Chitti, and A. Shalaby, "Understanding the drivers of transit construction costs in Canada: A comparative study," in *Canada's Urban Infrastructure Deficit: Toward Democracy and Equitable Prosperity,* Toronto, ON, Canada: University of Toronto School of Cities, 2025. [Online]. Available: https://schoolofcities.utoronto.ca/wp-content/uploads/2025/04/Understanding-the-Drivers-of-Transit-Construction-Costs-in-Canada_Feb-2025_FINAL.pdf

[52] J. G. Allen, "Choice of current and voltage for North American commuter rail electrifications," *Transp. Res. Rec.: Journal of the Transportation Research Board,* vol. 2678, no. 10, pp. 1303–1326, 2024, https://doi.org/10.1177/03611981241236788.

[53] *Canadian Electrical Code,* Part I, CSA C22.1 (26th ed.), Safety Standard for Electrical Installations, Canadian Standards Association, Toronto, ON, Canada, 2024. [Online]. Available: https://www.csagroup.org/store/product/CSA_C22.1%3A24

[54] *Railway Electrification Guidelines,* CAN/CSA-C22.3 NO. 8-M91 (R2003), Canadian Standards Association, Toronto, ON, Canada, 2003. [Online]. Available: https://www.csagroup.org/store/product/2412616

[55] IEEE Standards Association. "IEEE VTS Traction Power Systems Standards Committee (VTS/TPSSC)." Accessed: Mar. 28, 2025. [Online]. Available: https://sagroups.ieee.org/vt-tpssc

[56] IEEE Standards Association, "2022 IEEE power, distribution and regulating transformers collection," IEEE Standards Association, New York, NY, United States, 2022. [Online]. Available: https://standards.ieee.org/wp-content/uploads/import/documents/tocs/powerdistribution.pdf

[57] IEEE Standards Association, "IEEE power switchgear, circuits and fuses standards collection: VuSpec," IEEE Standards Association, New York, NY, United States, 2018. [Online]. Available: https://standards.ieee.org/wp-content/uploads/import/documents/tocs/switchcircfuses.pdf

[58] J. C. Webb, B. S. Valiyattil, T. Neighbours, and H. Karandikar, "IEC vs. IEEE/ANSI medium voltage switchgear: Which one Should You Use and Does it Matter?" in *2019 IEEE Petroleum and Chemical Industry Committee Conference (PCIC),* Vancouver, BC, Canada, 2019, pp. 285–292. [Online]. Available: https://doi.org/10.1109/PCIC30934.2019.9074491

[59] Schneider Electric, "MV technical guide," Schneider Electric, Rueil-Malmaison, France, 2017. Accessed: Apr. 9, 2025. [Online]. Available: https://ckm-content.se.com/ckmContent/sfc/servlet.shepherd/document/download/0698V00000jNfruQAC

[60] *Traction Electrification Distribution System Inspection, Maintenance and Testing,* APTA RT-FS-S-006-03, Rev. 2, American Public Transportation Association, Washington, DC, United States, 2017. [Online]. Available: https://www.apta.com/wp-content/uploads/Standards_Documents/APTA-RT-FS-S-006-02-Rev-2.pdf

[61] American Public Transportation Association. "About APTA: Our purpose." [Online]. Available: https://www.apta.com/about/our-purpose

[62] *Overhead Systems,* CSA C22.3 NO. 1, Canadian Standards Association, Toronto, ON, Canada, 2020. [Online]. Available: https://www.csagroup.org/store/product/CSA%20C22.3%20NO.%201:20

[63] *Overhead Transmission Lines – Design Criteria (Adopted IEC 60826:2017, Fourth Edition, 2017–02, with Canadian Deviations),* CSA C22.3 NO. 60826 (R2023), Canadian Standards Association, Toronto, ON, Canada, 2019. [Online]. Available: https://www.csagroup.org/store/product/CSA%20C22.3%20NO.%2060826%3A19

[64] *Alberta Electrical Utility Code,* Sixth Edition, Safety Codes Council, Edmonton, AB, Canada, 2022. [Online]. Available: https://ebs.safetycodes.ab.ca/documents/webdocs/PI/2022_AEUC.pdf

[65] Association of American Railroads, "Study of catenary electrification of the North American Class I railroad network," Association of American Railroads, Washington, DC, United States, Feb. 2025. [Online]. Available: https://www.aar.org/wp-content/uploads/2025/02/Final-Electrification-Report-02252025.pdf

[66] *Maintenance of Electrical Systems,* CSA Z463, Canadian Standards Association, Toronto, ON, Canada, 2024. [Online]. Available: https://www.csagroup.org/store/product/CSA_Z463%3A24

[67] *IEEE Guide for Rail Potential Management for DC Electrification Systems,* IEEE 2720–2021, IEEE, Piscataway, NJ, United States, 2021. [Online]. Available: https://doi.org/10.1109/IEEESTD.2021.9450066

[68] Engineers Canada. "Public guideline on the practice of engineering in Canada: Fundamental principles." Accessed: Apr. 10, 2025. [Online]. Available: https://engineerscanada.ca/guidelines-and-papers/public-guideline-on-the-practice-of-engineering-in-canada#-fundamental-principles

[69] National Society of Professional Engineers. "What is a PE?" Accessed: Apr. 10, 2025. [Online]. Available: https://www.nspe.org/about/about-professional-engineering/what-pe

[70] Metrolinx, "Reliability, availability and maintainability (RAM) analysis report: Product description," Metrolinx, Toronto, ON, Canada, Rep. MX-SEA-PD-120, 2023. [Online]. Available: https://assets.metrolinx.com/image/upload/v1737991310/Documents/Engineering/MX-SEA-PD-120_RAM_Analysis_Report_PD.pdf

[71] E. Abotalebi, Y. Zhao, A. Raj, and J. G. Petrunić, "Rail innovation in Canada: Top 10 technology areas for passenger and freight rail," Canadian Urban Transit Research and Innovation Consortium, Toronto, ON, Canada, 2020. [Online]. Available: https://cutric-crituc.org/wp-content/uploads/2020/06/FINAL-Rail-Innovation-in-Canada-Top-10-Technology-areas-for-Passenger-and-Freight-Rail-EA-2.pdf

[72] M. Shurland and P. Raj, "Rail decarbonization: A global collaborative research endeavor," Federal Railroad Administration, United States Department of Transportation, Washington, DC, United States, 2024. [Online]. Available: https://railroads.dot.gov/sites/fra.dot.gov/files/2024-09/Rail%20Decarbonization.pdf

[73] Association of American Railroads, "Oppose rail electrification and support sensible climate policy," Association of American Railroads, Washington, DC, United States, 2021. [Online]. Available: https://www.railwayage.com/wp-content/uploads/2021/02/AAR-Electrification-Fact-Sheet.pdf

[74] J. Allan and I. Mudalige, "Shortline Project: Bringing back regional rail to Alberta, Canada," Integrated Travel Research and Development, Airdrie, AB, Canada, 2024. [Online]. Available: https://www.researchgate.net/publication/379890435_SHORTLINE_PROJECT_Bringing_back_regional_rail_to

[75] T. Boray, M. Hegazi, H. Busche, and G. Lovegrove, "The economic feasibility of (re-)introducing tram-trains in Canada: Okanagan Valley electric regional passenger rail," *Sustainability,* vol. 16, no. 10, 2024, Art. no. 4081, https://doi.org/10.3390/su16104081.

[76] É. Cantin-Nantel. "Can Canada finally build high-speed rail without it becoming an expensive, delayed, overbudget boondoggle?" The Hub. Accessed: Jan. 2025. [Online]. Available:https://thehub.ca/2024/12/05/can-canada-finally-build-high-speed-rail-without-it-becoming-an-expensive-delayed-overbudget-boondoggle-transit-experts-weigh-in

[77] D. Penner. "SkyTrain's $2-billion overrun part of a national trend of budget-busting." Vancouver Sun. Accessed: Jan. 2025. [Online]. Available: https://vancouversun.com/news/skytrains-2-billion-overrun-part-of-a-national-trend

[78] C. Plante. "REM price tag will jump to $9.4 billion, Quebec's auditor general says." The Gazette. [Online]. Available: https://montrealgazette.com/news/local-news/rem-price-tag-will-jump-to-9-4-billion-quebecs-auditor-general-says

[79] Business Council of Alberta. "Off the rails: How Canada's urban rail construction costs compare to other countries." [Online]. Available: https://businesscouncilab.com/insights-category/economic-insights/off-the-rails-how-canadas-urban-rail-construction-costs-compare-to-other-countries

[80] O. Moore and J. Gray. "Canadian transit projects, mired in delays and cost overruns, force a rethink on what's gone wrong." The Globe and Mail. Accessed: Feb. 2025. [Online]. Available: https://www.theglobeandmail.com/canada/article-canadian-transit-projects-mired-in-delays-and-cost-overruns-force-a

[81] M. Siemiatycki, "Cost overruns on infrastructure projects: Patterns, causes, and cures," *IMFG Perspectives,* no. 11, 2015. [Online]. Available: https://utoronto.scholaris.ca/server/api/core/bitstreams/1788d8cc-f385-472a-ae21-14e0a64631c5/content

[82] Federal Railroad Administration, "FRA guidance on development and implementation of railroad capital projects," Federal Railroad Administration, United States Department of Transportation, Washington, DC, United States, 2023. Accessed: Jan. 2025. [Online]. Available: https://railroads.dot.gov/elibrary/fra-guidance-development-and-implementation-railroad-capital-projects

[83] P. Nouaille *et al.,* "Recommandations pour l'évaluation socio-économique des projets de transport collectif sous maîtrise d'ouvrage locale," Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement (Cerema), Bron, France, 2021. [Online]. Available: https://www.cerema.fr/fr/centre-ressources/boutique/recommandations-evaluation-socio-economique-projets

[84] *Workplace Electrical Safety,* CSA Z462, Canadian Standards Association, Toronto, ON, Canada, 2021. [Online]. Available: https://www.csagroup.org/store/product/CSA%20Z462%3A21

[85] D. Lebeau, "Arc flash hazards on direct current (DC) systems," BBA, Mont-Saint-Hilaire, QC, Canada, 2017. Accessed: Jan. 2025. [Online]. Available: https://www.bbaconsultants.com/publications/arc-flash-hazard-on-direct-current-dc-systems

[86] T. Augustine *et al.,* "Ready for green jobs: How ready are Canadian regions to attract and support the skilled workforce needed to reach climate targets and drive clean growth?" The PLACE Centre, Smart Prosperity Institute, Ottawa, ON, Canada, Jun. 2023. [Online]. Available: https://fsc-ccf.ca/research/ready-for-green-jobs

[87] ECO Canada. "2023 environmental job postings trends in review: The ebbs and flows of Canada's environmental job market." Accessed: Jan. 2025. [Online]. Available: https://eco.ca/research-and-resources/environmental-job-market-trends

[88] Sia Partners, "Navigating the landscape of green jobs," Sia Partners, Paris, France, Apr. 2024. [Online]. Available: https://www.sia-partners.com/system/files/document_download/file/2024-04/2024%20Green%20Jobs.pdf

[89] Railway Association of Canada. "Railway training." Accessed: Jan. 2025. [Online]. Available: https://www.railcan.ca/careers/railway-training

[90] VIA Rail. "Locomotive engineer apprenticeship program." Accessed: Jan. 2025. [Online]. Available: https://corpo.viarail.ca/en/locomotive-engineer-apprentice

[91] Canadian Heartland Training Railway. "Industrial railway training." Accessed: Jan. 2025. [Online]. Available: https://chtr.ca/industrial-railway-training

[92] BCIT. "School of Transportation: Railway training." Accessed: Jan. 2025. [Online]. Available: https://www.bcit.ca/transportation/areas-of-study/motive-power/railway-training

[93] Ontario Tech University. "Railway engineering specialization." Accessed: Jan. 2025. [Online]. Available: https://partners.ontariotechu.ca/industry-lead-initiatives/railway-engineering-specialization

[94] McMaster University. "SEP 736/Railway electrification infrastructure and technology." 2025. [Online]. Available: https://academiccalendars.romcmaster.ca/preview_course_nopop.php?catoid=55&coid=276838

[95] CENELEC. "The Frankfurt Agreement: CENELEC cooperation with IEC." [Online]. Available: https://www.cencenelec.eu/about-cenelec/cenelec-and-iec-cooperation

[96] International Electrotechnical Commission. "TC 9: Electrical equipment and systems for railways, – TC 9 subgroups." Accessed: Apr. 7, 2025. [Online]. Available: https://www.iec.ch/dyn/www/f?p=103:29:108534445637128::::FSP_ORG_ID,FSP_LANG_ID:1248,25#1

[97] Standards Council of Canada. "IEC honours six experts representing Canada." [Online]. Available: https://scc-ccn.ca/resources/news/iec-honours-six-experts-representing-canada

[98] Transport Canada. "6. PIC – Passenger prioritization." [Online]. Available: https://tc.canada.ca/en/binder/6-pic-passenger-prioritization

[99] C. Reynolds. "Via Rail CEO calls for right of way over freight trains, passenger bill of rights." The Canadian Press. [Online]. Available: https://www.thecanadianpressnews.ca/politics/via-rail-ceo-calls-for-right-of-way-over-freight-trains-passenger-bill-of-rights/article_77ae97a6-2f99-578a-8185-44fe39bc263b.html

[100] Government of Canada, 44th Parliament, 1st session, Dec. 13, 2023. *Bill C-371, An Act to amend the Canada Transportation Act (passenger rail service).* [Online]. Available: https://www.parl.ca/LegisInfo/en/bill/44-1/C-371

[101] WSP. "Waterloo Region rapid transit." Accessed: Feb. 21, 2025. [Online]. Available: https://www.wsp.com/en-ca/projects/waterloo-region-rapid-transit

[102] J. Weidner. "Derail switches installed to protect Ion infrastructure from oversized freight trains." Waterloo Region Record. Accessed: Feb. 21, 2025. [Online]. Available: https://www.therecord.com/news/waterloo-region/derail-switches-installed-to-protect-ion-infrastructure-from-oversized-freight-trains/article_9bbe5cc7-6a8c-52e9-9e2c-7d473273c9f4.html

[103] Urban Transport Magazine. "Waterloo (Canada) opens new light rail line." Accessed: Feb. 21, 2025. [Online]. Available: https://www.urban-transport-magazine.com/en/waterloo-canada-opens-new-light-rail

[104] E. Sela, R. R. Resor, and T. R. Hickey, "Shared-use corridors survey of current practice and recommendations for the future," in *Transportation Research Circular E-C058: 9th National Light Rail Transit Conference,* Portland, OR, United States, Nov. 16–18, 2003, pp. 300–315. Accessed: 2025. [Online]. Available: https://trb.org/publications/circulars/ec058/08_04_Sela.pdf

[105] Canadian Standards Association, "The municipal how-to guide for CSA community water standards," Canadian Standards Association, Toronto, ON, Canada, 2024. [Online]. Available: https://dev-www.csagroup.org/wp-content/uploads/CSA-Group_WaterStandards-HowToGuide-EN-2024_Accessible.pdf

[106] Canadian Standards Association, "Helping manufacturers bring electric vehicle supply equipment (EVSE) to international markets," Canadian Standards Association, Toronto, ON, Canada, 2024. [Online]. Available: https://www.csagroup.org/wp-content/uploads/CSA-EVSE-Brochure-Global-EN_Press.pdf

[107] American Railway Engineering and Maintenance-of-Way Association. "AREMA position paper: Standards for the design, construction and maintenance of high speed rail (HSR) systems." Accessed: Oct. 2025. [Online]. Available: https://arema.org/AREMA_MBRR/AREMA_MBRR/High_Speed_Rail_Policy.aspx

[108] American Railway Engineering and Maintenance-of-Way Association, "High speed rail systems," in *2025 Manual for Railway Engineering,* Volume 3, Lanham, MD, United States: American Railway Engineering and Maintenance-of-Way Association, 2025, ch. 17. [Online]. Available: https://publications.arema.org/Publication/MRE_2025

[109] CN. "CN advances sustainability efforts with Wabtec's battery-electric locomotive." [Online]. Available: https://www.cn.ca/en/news/2021/11/cn-advances-sustainability-efforts-with-wabtecs-battery-electric

[110] CPKC. "ATCO EnPower and CPKC complete construction of two hydrogen production and refuelling stations in Alberta." [Online]. Available: https://www.cpkcr.com/content/cpkc/ca/en/media/Atco-empower.html

[111] Metrolinx, "GO Expansion: Full business case," Metrolinx, Toronto, ON, Canada, 2018. [Online]. Available: https://assets.metrolinx.com/image/upload/v1667497052/Images/Metrolinx/GO_Expansion_FBC.pdf

[112] Standards Council of Canada. "Sub-programs: Independent Safety Assessor for Railway Systems." Accessed: Aug. 2025. [Online]. Available: https://scc-ccn.ca/accreditation/accreditation-programs/inspection-bodies/independent-safety-assessor-railway-systems

Appendix A – Studied Standards

Table A1: Standards Included in the Literature Review and Gap Analysis

Organization	Area(s)	Standard/Guidelines	Year	Scope of Application	Topics Covered
CSA Group	Traction Power Substations (TPSS) Power Transmission and Distribution Overhead Catenary Systems (OCS) Grounding and Bonding	CAN/CSA-C22.3 NO. 8-M91, *Railway Electrification Guidelines*	2003	AC, 25 kV, 2x25 kV, 50 kV	▪ Electrical insulation characteristics of high voltage switchgear and transformers ▪ Maintenance of traction power components ▪ Workplace electrical safety and hazards ▪ Electric supply and communication lines and equipment (outside of buildings and fenced supply stations) ▪ Overhead transmission lines ▪ General requirements for electric circuits safety ▪ Grounding and bonding for OCS, supply systems less than or equal to 22 kV ▪ Grounding of railway equipment and adjacent structures and environment
		CSA C22.1, *Canadian Electrical Code, Part I, Safety Standard for Electrical Installations*	2024	OCS design guidelines from 50 to 300 km/h	
		CSA Z463, *Maintenance of Electrical Systems*	2024	Electrical safety arcing in DC up to 600 V	
		CSA Z462, *Workplace Electrical Safety*	2021	Electric system	
		CSA C22.3 NO. 1, *Overhead Systems*	2020	OCS	
		CSA C22.3 NO. 60826, *Overhead Transmission Lines – Design Criteria (Adopted IEC 60826, fourth edition, 2017-02, with Canadian deviations)*	2023	Design criteria for overhead transmission lines	
AREMA	TPSS Power Transmission and Distribution OCS Grounding and Bonding	*Manual for Railway Engineering*, Volume 3: Infrastructure and Passenger (Chapters 17, 28, and 33)	2024	DC, 25 kV AC HSR	▪ Traction power supply requirements for railroad AC electrification systems ▪ Traction power supply and distribution requirements for DC rail transportation systems ▪ Guidelines for propulsion systems in high-speed rail (HSR) ▪ Distribution requirements for DC and AC rail transportation systems ▪ Ancillary systems: communications, illumination, wayside and standby power systems ▪ Foreign HSR technical capabilities and operating characteristics ▪ Traction electrification system grounding and bonding for AC and DC ▪ Possible effects of electrolytic corrosion due to stray currents from track rails must be addressed, especially with DC power (in AC systems, the effects of stray currents is considered to be minimal, but still needs to be checked)
		Practical Guide to Railway Engineering, Chapter 9: Railway Electrification	2019	OCS 3rd rail	

Organization	Area(s)	Standard/Guidelines	Year	Scope of Application	Topics Covered
IEC	Power Transmission and Distribution	IEC 60715, *Dimensions of low-voltage switchgear and control gear – Standardized mounting on rails for mechanical support of switchgear, controlgear and accessories*	2017	Protection principles for AC and DC electric traction power supply DC and AC switchgear Low voltage switchgear and control gear Surge arresters Voltage limiting devices Electromagnetic compatibility	▪ Dimensions of mounting for low voltage switchgear and control gear ▪ Functional requirements ▪ Standards dimensions ▪ DC switchgear and control gear; DC switchgear assemblies; DC circuit breakers; indoor and outdoor DC disconnectors, switch-disconnectors and earthing switches; ▪ Surge arresters and low voltage limiters for specific use in DC ▪ Non-linear metal-oxide surge arresters without gaps ▪ Service requirements ▪ Characteristics of the unit ▪ Construction ▪ Information and marking ▪ Information to be exchanged between purchaser and supplier ▪ Measurement, control and protection devices for specific use in DC traction systems ▪ Isolating voltage transducers and other voltage measuring devices ▪ Isolating current transducers and other current measuring devices ▪ Electromagnetic compatibility for railways systems ▪ Emission limits ▪ EM emission measurements ▪ Signalling and telecommunication ▪ AC switchgear ▪ Circuit breakers above 1 kV ▪ Disconnectors, earthing switches and switches above 1 kV ▪ Measurement, control and protection devices in AC traction ▪ Single-phase current and voltage transformers ▪ Other devices ▪ Clearances and creepage distances for all electrical and electronic equipment ▪ Basis for insulation coordination ▪ Requirements and dimensioning rules for clearances ▪ Dimensioning rules for creepage distances ▪ Tests (up to 320 km/h, type, routine, acceptance) and measurements ▪ Specific requirements for applications in the railway field ▪ Shortest durations of overvoltages ▪ Arrester classification ▪ Voltage limiting devices ▪ Classes of voltage limiting devices ▪ Characteristics and requirements of voltage limiting devices ▪ Protection for safety ▪ Electric shock ▪ Thermal effects ▪ Against overcurrent ▪ Voltage disturbances and electromagnetic disturbances
		IEC 61992-1, *Railway applications – Fixed installations – DC switchgear – Part 1: General*	2014		
		IEC 61992-2, *Railway applications – Fixed installations – DC switchgear – Part 2: DC circuit-breakers*	2014		
		IEC 61992-3, *Railway applications – Fixed installations – DC switchgear – Part 3: Indoor DC disconnectors, switch-disconnectors and earthing switches*	2015		
		IEC 61992-4, *Railway applications – Fixed installations – DC switchgear – Part 4: Outdoor DC disconnectors, switch-disconnectors and earthing switches*	2015		
		IEC 61992-5, *Railway applications – Fixed installations – DC switchgear – Part 5: Surge arresters and low-voltage limiters for specific use in DC systems*	2006		
		IEC 61992-6, *Railway applications – Fixed installations – DC switchgear – Part 6: DC switchgear assemblies*	2006, 2014, 2020		
		IEC 61992-7 series, *Railway applications – Fixed installations – DC switchgear – Part 7: Measurement, control and protection devices for specific use in DC traction systems*	2006		
		IEC 62236 series, *Railway applications – Electromagnetic compatibility*	2018		
		IEC 62505 series, *Railway applications – Fixed installations – Particular requirements for AC switchgear*	2016		
		IEC 62497-1, *Railway applications – Insulation coordination – Part 1: Basic requirements – Clearances and creepage distances for all electrical and electronic equipment*	2010		
		IEC 62497-2, *Railway applications – Insulation coordination – Part 2: Overvoltages and related protection*	2010		
		IEC 62848-1, *Railway applications – DC surge arresters and voltage limiting devices – Part 1: Metal-oxide surge arresters without gaps*	2016		
		IEC 62848-2, *Railway applications – DC surge arresters and voltage limiting devices – Part 2: Voltage limiting devices*	2019		
		IEC 60364, *Low-voltage electrical installations – Part 1: Fundamental principles, assessment of general characteristics, and definitions*	2005		
		IEC 61000-1-1, *Electromagnetic compatibility (EMC) – Part 1-1: General – Application and interpretation of fundamental definitions and terms*	2023		

Organization	Area(s)	Standard/Guidelines	Year	Scope of Application	Topics Covered
IEC		IEC 62305-1, *Protection against lightning – Part 1: General principles*	2024		**Lightning:** ▪ Threat, risk, protection, protection measures ▪ Electric traction power supply systems protection ▪ System to be protected; general principles ▪ Specific requirements of different systems (AC and DC) ▪ Limitations and residual risk ▪ Design verification
		IEC 63438, *Railway applications – Fixed installations – Protection principles for AC and DC electric traction power supply systems*	2024		
		IEC 60850, *Railway applications – Supply voltages of traction systems*	2014		
IEC	OCS	IEC 60913, *Railway applications – Fixed installations – Electric traction overhead contact lines systems*	2024	DC and AC overhead current collectors Light rail Heavy rail HSR	▪ Pantograph and overhead contact line system ▪ Technical requirements ▪ Marking ▪ Tests ▪ Inspection plan ▪ Reliability ▪ Maintenance ▪ Measurement of performance
		IEC 60494-1 and IEC 60494-2, *Railway applications – Rolling stock – Pantographs – Characteristics and tests – Part 1: Pantographs for main line vehicles, and Part 2: Pantographs for metros and light rail vehicles*	2013		
		IEC 62846, *Railway applications – Current collection systems – Requirements for and validation of measurements of the dynamic interaction between pantograph and overhead contact line*	2016		
		IEC 62486, *Railway applications – Current collection systems – Technical criteria for the interaction between pantograph and overhead contactline (to achieve free access)*	2017		
IEC **Disadvantages**	Grounding and Bonding	IEC 62128 series, *Railway applications – Fixed installations – Electrical safety, earthing and the return circuit*	2013	Mutual interaction of AC and DC electric traction power DC and AC switchgear Low voltage switchgear and control gear Surge arresters Voltage limiting devices Electromagnetic compatibility	▪ Electrical safety, earthing and the return circuit ▪ Clearances and creepage distances for all electrical and electronic equipment ▪ Technical requirements ▪ Shortest durations of overvoltages ▪ Marking ▪ Tests ▪ Inspection plan ▪ Reliability ▪ Maintenance ▪ Measurement of performance
		IEC 62497-1 and IEC 62497-2, *Railway applications – Insulation coordination – Part 1: Basic requirements – Clearances and creepage distances for all electrical and electronic equipment,* and *Part 2: overvoltages and related protection*	2010		
		IEC 62848-1, *Railway applications – DC surge arresters and voltage limiting devices – Part 1: Metal-oxide surge arresters without gaps*	2016		
		IEC 62848-2, *Railway applications – DC surge arresters and voltage limiting devices – Part 2: Voltage limiting devices*	2019		
		IEC 60364-1 and IEC 60364-4, *Low-voltage electrical installations – Part 1: Fundamental principles, assessment of general characteristics, and definitions, and Part 4: Protection for safety*	2005		
		IEC 61000, *Electromagnetic compatibility (EMC)*	2024		
		IEC 62305, *Protection against lightning*	2024		

Organization	Area(s)	Standard/Guidelines	Year	Scope of Application	Topics Covered
IEEE	TPSS	IEEE 519, *IEEE Standard for Harmonic Control in Electric Power Systems*	2022	DC traction Point of common coupling system Traction power design modelling Battery Energy feedback systems DC surge arresters, transient overvoltage protection, lightning Metal-oxide varistor gapless-surge arresters DC power up to 3200 V	**Point of common coupling system:** ▪ Design of power systems with nonlinear loads ▪ Negative effects of harmonics **Traction power:** ▪ Modelling and validation; analysis ▪ Material rating and use (cable); substation rating and placement ▪ Train voltages ▪ Energy storage for power demand variation ▪ Common terminology used to describe performance; common applications and technologies; common equipment topologies ▪ Specification of energy storage systems ▪ Economic considerations and cost-benefit analysis; modelling and simulation ▪ Performance and functional considerations; interoperability considerations ▪ Tools and methods to verify safety; tools and methods to measure and verify system performance ▪ Installation and integration considerations **Energy feedback system for DC traction power supply system:** ▪ Energy consumption; energy feedback; and energy storage ▪ DC surge arresters; transient overvoltage protection; design and application of dc surge arresters ▪ Power circuit breaker switchgear; power circuit breakers
		IEEE 1653.3, *IEEE Guide for Rail Transit Traction Power Systems Modeling*	2021		
		IEEE 1887, *IEEE Guide for Wayside Energy Storage Systems for DC Traction Applications*	2017		
		IEEE 2657, *IEEE Guide for Energy Feedback System for DC Traction Power Supply System*	2021		
		IEEE 1627, *IEEE Standard for Transient Overvoltage Protection of DC Electrification Systems by Application of DC Surge Arresters*	2019		
		IEEE C37.14, *Standard for DC (3200 V and below) Power Circuit Breakers Used in Enclosures*	2015		
		IEEE C37.20.1, *IEEE Standard for Metal-Enclosed Low-Voltage (1000 Vac and below, 3200 Vdc and below) Power Circuit Breaker Switchgear*	2015		
IEEE	Power Transmission and Distribution	IEEE 1653.3, *IEEE Guide for Rail Transit Traction Power Systems Modeling*	2021	Power transformers: ▪ 112.5 kVA through 10 000 kVA three-phase ▪ 250 kVA through 6667 kVA single-phase ▪ High voltage 69 000 V and below, and low voltage 34 500 V and below DC traction DC surge arresters Traction power rectifier transformers	**Traction power modelling:** ▪ Modelling and validation; analysis ▪ Material rating and use (cable); substation rating and placement ▪ Train voltages ▪ Energy storage for power demand variation ▪ Substation transformers ▪ Energy feedback system for DC traction power supply system ▪ Traction power rectifier transformers ▪ DC surge arresters; transient overvoltage protection ▪ Liquid-immersed power transformers and autotransformers
		IEEE 1887, *IEEE Guide for Wayside Energy Storage Systems for DC Traction Applications*	2017		
		IEEE C57.12.36, *IEEE Standard Requirements for Liquid-Immersed Distribution Substation Transformers*	2017		
		IEEE 2657, *IEEE Guide for Energy Feedback System for DC Traction Power Supply System*	2021		
		IEEE 1653.1, *IEEE Standard for Traction Power Rectifier Transformers for Substation Applications up to 1500 V DC Nominal Output*	2016		
		IEEE 1627, *IEEE Standard for Transient Overvoltage Protection of DC Electrification Systems by Application of DC Surge Arresters*	2019		
		IEEE C57.12.10, *IEEE Standard Requirements for Liquid-Immersed Power Transformers*	2017		
		IEEE 1653.2, *IEEE Standard for Uncontrolled Traction Power Rectifiers for Substation Applications up to 1500 V DC Nominal Output*	2020		

Organization	Area(s)	Standard/Guidelines	Year	Scope of Application	Topics Covered
IEEE	OCS	IEEE 1629, *IEEE Standard for Performance of DC Overhead Current Collectors for Rail Transit Vehicles*	2013	DC OCS systems Light rail Heavy rail HSR	▪ OCS performance requirements ▪ OCS for HSR ▪ Test methods for performance evaluation ▪ Pantograph off-line: overvoltage; harmonics ▪ Design of OCS for DC transit (new and retrofit) ▪ Performance requirements and design guidelines ▪ Safety ▪ System reliability ▪ Modes of operation ▪ Type of vehicle to be used ▪ Maintenance factors ▪ Identification of contact wire for OCS ▪ Maintenance practices for OCS for heavy rail, light rail, and trolley bus systems
		IEEE 2753, *IEEE Guide for Measurement of Pantograph Off-line and Evaluation of Current Collection Performance for High-Speed Railway*	2022		
		IEEE 1833, *IEEE Guide for Design of Direct Current Overhead Contact Systems for Transit Systems*	2023		
		IEEE 1896, *IEEE Standard for Identification of Contact Wire Used in Overhead Contact Systems*	2016		
		IEEE 1628, *IEEE Recommended Practice for Maintenance of DC Overhead Contact Systems for Transit Systems*	2009		
IEEE	Grounding and Bonding	IEEE 2720, *IEEE Guide for Rail Potential Management for DC Electrification Systems*	2021	DC systems Grounding of trains	▪ Rail potential management ▪ Stray current: method of synchronous monitoring ▪ DC equipment enclosures grounding ▪ Multi-point mobile grounding system requirement of grounding system for vehicles operation
		IEEE 2970, *IEEE Guide for Synchronous Monitoring of the Magnitude and Distribution of Stray Current in Urban Rail Transit's Direct Current Traction System*	2024		
		IEEE 1653.6, *IEEE Recommended Practice for Grounding of DC Equipment Enclosures in Traction Power Distribution Facilities*	2018		
		IEEE 2752, *IEEE Guide for Multi-Point Grounding System of Trains in Electrified Railway*	2023		
APTA	1.9–22kW [8]	APTA-PR-E-S-010-98, *Standard for the Development of an Electromagnetic Compatibility Plan*	1998	Electromagnetic compatibility Traction power and distribution maintenance Battery and backup power OCS 3rd rail DC traction Maintenance	▪ Electromagnetic compatibility program ▪ Frequency of tasks ▪ Qualification of personnel ▪ Tools, PPE ▪ Inspection, maintenance and testing ▪ Correction of deficiencies ▪ Traction electrification distribution system inspection maintenance testing ▪ Traction power maintenance training for power transmission and distribution, 3rd rail ▪ Inspection and maintenance ▪ Rail transit vented standby battery backup systems and uninterruptible power supplies ▪ 3rd rail collection equipment; frequency of tasks ▪ DC traction electrification substations maintenance
		APTA RT-FS-S-006-03, *Traction Electrification Distribution System Inspection, Maintenance and Testing*	2017		
		APTA-RT-RMT-RP-004-10, *Traction Power Maintenance Training Standards*	2010		
		APTA-RT-SC-RP-018-03, *Recommended Practice for Vented Standby Battery Backup System Inspection and Maintenance*	2004		
		APTA-RT-VIM-S-001-02, *Third Rail Current Collection Equipment Periodic Inspection and Maintenance*	2013		
		APTA RT-FS-S-004-03, *Traction Electrification Substation Inspection, Maintenance and Testing*	2017		

Organization	Area(s)	Standard/Guidelines	Year	Scope of Application	Topics Covered
APTA	OCS	APTA RT-FS-S-006-03, *Traction Electrification Distribution System Inspection, Maintenance and Testing*	2017	AC and DC systems AC: +600 V DC: 600 V to 1500 V	▪ Maintenance procedures ▪ Pantograph current collection ▪ Traction electrification distribution systems ▪ Maintenance training for staff ▪ Maintenance procedures
		APTA-RT-RMT-RP-004-10, *Traction Power Maintenance Training Standards*	2010		
		APTA-RT-VIM-S-002-02, *Pantograph Current Collection Equipment Periodic Inspection and Maintenance*	2013		
APTA	Grounding and Bonding	APTA RT-FS-S-005-03, *Traction Electrification Stray Current/Corrosion Control Equipment Inspection and Maintenance*	2017	AC and DC systems	▪ Stray current corrosion ▪ System equipment inspection and maintenance
		APTA-RT-SC-S-019-03, *Standard for AC Power Supply Ground Detection Inspection, Testing and Maintenance*	2004		
		APTA-RT-SC-S-020-03, *Standard for DC Power Supply Ground Detection Inspection, Testing and Maintenance*	2004		

Appendix B – Industry Engagement Phase

B.1 Online Survey

Prior to the surveys and interviews, participants were sent a form that presented the goal of the study, which was to identify gaps in the rail electrification industry. The form highlighted that participation was voluntary and could be withdrawn at any time, and that all the information provided by participants would be kept confidential. Data and responses would be aggregated based on the studied topics to avoid attributing comments to specific individuals or organizations.

The survey was presented using a web platform accessible to anyone with the link. The questions were as follows:

Railway Projects

1. In what geographic area are the rail projects located for your organization?
2. What kind of rail projects fall under your scope of work or jurisdiction?
3. At what voltage level do the projects you have worked on operate?

Codes and Standards

4. Does your organization work with codes and standards for railway projects in any way?
5. What codes and standards does your organization use for different components of railway infrastructure?
6. In particular, what codes and standards does your organization use for the different types of components and topics related to railway electrification (multiple choice list).
7. If other types of codes and standards are used for these components by your organization, please mention them.
8. Please select the standards and guides your organization uses for railway projects from the following list (and/or adding relevant ones to the list) (multiple choice list).
9. Please select or propose the standards and guides your organization uses for Overhead Catenary Systems (multiple choice list).
10. Please select or propose the standards and guides your organization uses for Traction Power Substations (multiple choice list).
11. Please select or propose the standards and guides your organization uses for Power Transmission and Distribution (multiple choice list).
12. Please select or propose the standards and guides your organization uses for Grounding and Bonding (multiple choice list).

Identifying Gaps in Codes and Standards

13. Do international standards and guidelines cover the needs of the Canadian railway industry when it comes to railway electrification infrastructure?

14. Do you believe that there are gaps in the existing codes and standards related to Canadian railway electrification?

15. Why do existing standards and guidelines cover, or not, the needs of the Canadian railway electrification industry? Please explain.

16. In your opinion, for which systems do this standard and code gap exist?

17. Do you believe the Canadian railway industry will benefit from the availability of standardized solutions that address railway electrification infrastructure?

18. Please choose from the components of the railway electrification infrastructure wherein you feel additional standards are needed to be developed to address gaps (multiple choice list).

19. What parts of the railway projects and operations should be codified in Canada (multiple choice list)?

20. Please choose what areas of rail that standards should be developed for the Canadian railway electrification infrastructure (multiple choice list).

21. Please identify any impediments and challenges related to the railway electrification in Canada based on jurisdictional constraints/barriers.

Final Section: Comments and Recommendations

22. Can you recommend any specific studies or work relevant to the goal of this study for railway electrification?

23. Do you recommend a specific individual from your organization that will be relevant for this study?

24. Please, share any comment or recommendations on the current study, addressing the needs of electric railways in the next 5 to 10 years in Canada.

B.2 Interviews

The interview questions were asked to the participants and answers were noted as the interview progressed. Once the interview terminated, meeting notes were summarized into a document and sent to each participant to be validated for its use in the final research report. Interview sessions were scheduled for a duration of 1 h and held online.

The interview questions were as follows:

- What are the services that your organization provides?
- What are your responsibilities inside your organization?
- What specific experiences do you have in the railway field?
- How many years of experience does it represent?
- Which sector of the railway industry did you and do you work in (LRT, freight, passenger, HSR, etc.)?

Perspectives on Railway Electrification

- What are your thoughts on railway electrification in Canada?
- What are the main challenges to electrification that you see, think about, or have experienced in Canada?
- Is there any situation of railway electrification you experienced that is relevant to the study? Installation, construction, specific project?
- Can you think of any Canadian initiatives relevant to the scope of this current study?
- In your situation, does the rolling stock determine the traction power used or do you adapt vehicles to power supply?

Codes and Standards

- What are the main standards and codes used in your organization?
- Why do you use these standards in particular (historical projects, foreign context, American influence, client specification, specific regional code, etc.)?
- In your opinion, what challenges are related to the use of codes and standards in your projects?
- Do you believe that there is a standard and code gap in Canada? Or provincially/locally (CEC 22.1 adaptation)?
- If yes, in what domain/topic?
- How do you see this solved?
- Would you like to see a railway electrification code in Canada?
- If no, why?
- If a Canadian code is developed, on which local or international code would you prefer it be adapted from (i.e., do you see a good example that could be used)?
- How should this new standard be applied to the industry?
  - Regulatory (code)
  - Recommended
  - Guideline
- What should be the scope of work of the new standard?
  - Design
  - Equipment/material
  - Procurement
  - Inspection and maintenance
  - Training
  - Construction
- Are there any emerging topics or trends in railway electrification over the next 5 to 10 years that may necessitate the development of new standards or the revision of existing ones?

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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