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RAIL INNOVATION IN CANADA: Top 10 Technology Areas for Passenger and Freight Rail

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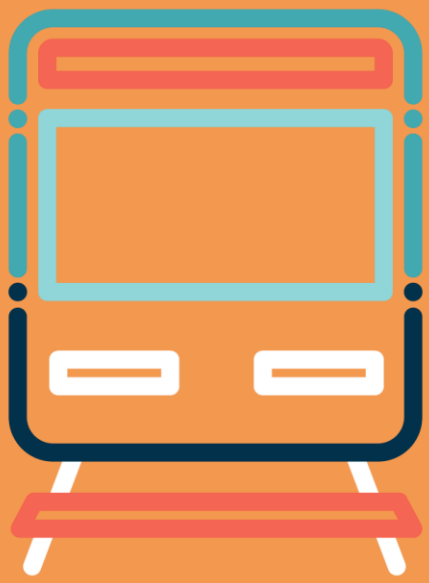

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Rail Innovation in Canada: Top 10 Technology Areas for Passenger and Freight Rail
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LIST OF ACRONYMS

AAR	Association of American Railroads
AI	Artificial intelligence
AM	Additive manufacturing
AREMA	American Railway Engineering and Maintenance-of-Way Association
CACs	Common air contaminants
CaRRL	Canadian Rail Research Laboratory
CBTC	Communications-based train control
CN	Canadian National Railway
CNY	Chinese Yuan
CP	Canadian Pacific Railway
CSA	Canadian Standards Association
DACH	Deutschland (Germany), Austria, Confoederatio Helvetica (Switzerland)
DB	Deutsche Bahn (German Rail)
DC	Direct current
ESS	Energy storage systems
EVID	Electric Vehicle Infrastructure Demonstration
FCEB	Fuel cell electric buses
FCEV	Fuel cell electric vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FRP	Fibre-reinforced plastic
GFRP	Glass-fibre-reinforced polymer
GHG	Greenhouse gas
GTA	Greater Toronto Area
GTHA	Greater Toronto and Hamilton Area
H2	Hydrogen
HSR	High-speed rail
HQP	Highly qualified personnel
ISED	Innovation, Science and Economic Development Canada
LH2	Liquid hydrogen
LNG	Liquefied natural gas
LRT	Light-rail transit
LRV	Light-rail vehicle
maglev	Magnetic levitation
MDO	Multidisciplinary design optimization
NREL	National Renewable Energy Laboratory
OEM	Original equipment manufacturers

RAC	Railway Association of Canada
RER	Regional Express Rail
R&D	Research and development
RGHRP	Railway Ground Hazard Research Program
SIF	Strategic Innovation Fund
STDC	Sustainable Technology Development Canada
TPAP	Transit Project Assessment Process
TRL	Technology-readiness level
TTC	Toronto Transit Commission
vactrain	Vacuum tube train
VUCA	Volatility, uncertainty, complexity and ambiguity

ABSTRACT

Transportation 2030: A Strategic Plan for the Future of Transportation in Canada, recognizes five themes to provide direction for future priorities for the Department. One of these priorities includes Green and Innovative Transportation. The Innovation Centre of Transport Canada launched the Rail Innovation Scan to provide the Department with focused avenues of technology investigation, consistent with Green and Innovative Transportation.

The Canadian Urban Transit Research and Innovation Consortium (CUTRIC) conducted the scan. The methodology relied on outputs from five focus group sessions that were conducted across Canada under the following subjects: alternative propulsion, energy efficiency, operational optimization and alternative materials. CUTRIC consulted with more than 220 participants representing dozens of companies and organizations in the rail sector, including academic researchers, rail operators, rail manufacturers, industry experts and government officials. The following "Top 10" list of feasible technology theme areas to build Canada's future rail passenger and freight mobility system were identified:

1. Catenary – free electrification of rail facilities
2. Hydrail passenger
3. CNG/Hydrogen to diesel complementation
4. Hydrail switching yards
5. 3D printing for rail spare parts
6. Artificial Intelligence for fleet management
7. A rail car demonstrator
8. A propulsion technology simulation tool
9. Toronto Union station flow and capacity
10. Rail electrification

RÉSUMÉ

Transports 2030 : un plan stratégique pour l'avenir des transports au Canada, définit cinq thèmes pour orienter les priorités futures du ministère, dont notamment le transport écologique et innovateur. Le Centre d'innovation de Transports Canada a lancé l'étude sur l'innovation ferroviaire afin de fournir au ministère des pistes d'études ciblées en matière de technologies d'intérêt pour le transport écologique et innovateur.

Le Consortium de recherche et d'innovation en transport urbain au Canada (CRITUC) a entrepris l'étude. La méthodologie s'est appuyée sur les résultats de cinq séances de groupes de discussion menées dans tout le Canada sur les sujets suivants : d'autres moyens de propulsion, l'efficacité énergétique, l'optimisation opérationnelle, et l'utilisation d'autres matériaux. Au cours de ces séances, le CRITUC a consulté plus de 220 participants représentant une douzaine de compagnies et d'organisations dans le secteur ferroviaire, y compris des chercheurs universitaires, des exploitants ferroviaires, des constructeurs ferroviaires, des experts d'industrie et des fonctionnaires. Voici la liste des 10 secteurs technologiques les plus réalistes pour bâtir l'avenir du réseau de transport de passagers et de marchandises au Canada:

1. Caténaires – électrification gratuite des installations ferroviaires
2. Passagers Hydrail
3. Complémentarité entre GNC/hydrogène et le diesel
4. Gares de triage de Hydrail
5. Impression 3D de pièces ferroviaires de rechange
6. Intelligence artificielle pour la gestion du parc
7. Démonstrateur de wagon
8. Outil de simulation des technologies de propulsion
9. Flux et capacité de la Gare Union de Toronto
10. Électrification du transport ferroviaire

EXECUTIVE SUMMARY

The main objective of the clean rail innovation study conducted by the Canadian Urban Transit Research and Innovation Consortium (CUTRIC) for Transport Canada is to identify the "Top 10" feasible technology theme areas that will build Canada's future passenger and freight mobility system. The overall goal is to conduct a preliminary scan of the state of the industry in Canada today—from both passenger and freight perspectives—in terms of technology innovation that Transport Canada could ultimately use to guide its medium- to long-term research, development and deployment (RD&D) efforts. As a fundamental part of this initiative, CUTRIC has integrated Canadian-based manufacturers and suppliers within the rail and mobility sectors across five national focus group sessions conducted throughout 2018 and 2019.

Over the course of these sessions, CUTRIC consulted with more than 220 participants representing dozens of companies and organizations in the rail sector, including academic researchers, rail operators, rail manufacturers, industry experts and government officials. These sessions identified major technology themes at play in rail innovation: alternative propulsion, energy efficiency, operational optimization and alternative materials.

As part of this initiative, two focus group sessions, focusing on alternative propulsion, were conducted at Queen's University in Kingston, Ontario, on November 22, 2018, and at the Metrolinx office in Toronto, Ontario, on February 11, 2019. The focus group session focusing on energy efficiency was conducted at the Ballard Power Systems office in Burnaby, British Columbia, on April 10, 2019. The session focusing on operational optimization took place at the University of Waterloo, Ontario, on June 3, 2019, and the session on alternative materials was held at Bombardier offices in St. Bruno, Quebec, on August 8, 2019.

This report provides detailed descriptions of each technology theme area proposed throughout the five focus group sessions, and the quantitative and qualitative reasons that enabled those theme areas to be ranked using a scale of "1" to "10". The report reviews the methodology, data collection process, focus group methodology, quantitative and qualitative data analysis, and summary of outcomes of the focus group sessions along with the resultant ranking. Recommendations are also provided for potential innovations in rail transportation and mobility beyond the "Top 10" list and the discussions within the sessions. These recommendations will be advantageous for building Canada's future passenger and freight mobility systems.

A literature review of global innovation in the rail sector is also included in this report, which demonstrates that Canada is lagging behind several developed and developing nations in the design, integration, launch and trial of alternative propulsion applications in the rail sector. A challenge exists in the minimal global commercialization of innovative technologies, including catenary-free battery electric system applications and hydrogen electric propulsion applications, despite Canada possessing advanced technological resources and expertise in these areas. There is, however, potential for Canada to lead in passenger and freight rail innovation, given the cross-pollination of several major companies in the shuttle, bus, coach, truck and rail sectors with regards to electrification of propulsion systems in this country.

To generate rankings for the "Top 10" rail innovation projects documented in this report, CUTRIC engaged in a three-step data-collection process. The first step involved identifying core themes of research and innovation relevant from a global perspective. These themes were extracted from a

preliminary literature review and shared with Transport Canada for feedback before being finalized. The second step involved semi-structured focus group methodologies to develop proposed technology theme areas. The third step involved a quantitative and qualitative analysis of the variables, emanating from the focus group sessions, using a non-weighted approach to tabulate four core variables (i.e. cost, timeline, technology readiness level (TRL) advancement, and number of stakeholders) in quantitative ranking, and developing a thematic coding methodology for qualitative analysis.

Table ES.1 shows results of the quantitative rankings integrating four quantitative variables identified above. These quantitative results suggest that most alternative propulsion projects are ranked at the top, while most of the alternative material projects are ranked lower by comparison. In the analysis, CUTRIC also determined that a project's ranking is not affected by the project's total cost. When removing cost as a variable, the same top three projects remain listed in the "Top 10" overall ranking.

CUTRIC also established five categories of qualitative thematic analysis, including "economic," "environment," "social," "operational" and "technological" variables, based on feedback from the focus groups. These qualitative findings add insights to quantitative rankings (i.e. proposed projects with similar quantitative ranking scores), and will help Transport Canada to identify the socioeconomic positioning of participants in specific technology theme groups throughout the consultation process.

Note that the existing report is a preliminary analysis aimed at generating an overview of the actual Canadian landscape in terms of rail technology innovation. Further detailed studies and deep-dive focus group sessions within each technology theme area are required to capture a full picture of rail innovation potential across Canada, and to determine whether high-level proposals for industry investment in the areas identified would, in fact, come to fruition were there to be targeted public policy levers in place to support such growth.

Table ES.1. Quantitative ranking of rail projects. Scores for each variable are shown in red.

Nominated project	Session	Sector	Cost (million $ CAD)/score	Final TRL/score	Number of years/score	Number of stakeholders/ score	Total score	Project rank
Catenary-Free Electrification Rail Facilities	1B	Industry	$10–$20	9	3	3	33	High "Top 10"
			6	10	7	10		
Hydrail Passenger	1B	Industry/Community	$350	9	4	5	30	
			10	10	4	6		
CNG/Hydrogen-to-Diesel Complementation	2	Academic	$10–$20	9	5	3	27	
			6	10	1	10		
Hydrail Switching Yards	1B	Industry	$250k–$50M	8	4	6	23+	Medium "Top 10"
			8	7	4	4		
3D Printing for Rail Parts	4	Industry	$5–$10	9	5	4	23	
			4	10	1	8		
Artificial Intelligence Fleet Management	2	Operators/ manufacturers	$5–$10	8	5	3	22	
			4	7	1	10		
Rail Car Demonstrator	4	Industry	$50–$100	7	6	5	21	
			10	4	1	6		
Propulsion Technology Simulation Tool	2	manufacturers / technology integrators	$3	6	1.5	6	17	Low "Top 10"
			2	1	10	4		
Toronto Union Station Flow and Capacity	3	Academic	$1	6	3	5	16	
			2	1	7	6		
Rail Electrification	2	Government/public sector	$10	7	5	5	15	
			4	4	1	6		
Hydrail Long Distance Freight	1B	Government/academic	$2–$100	6	5	9	14+	Outside the "Top 10"
			10	1	1	2		
Hybrid Light-weight Structure	4	Academic	$10	6	5	4	14	
			4	1	1	8		
Sandwiched Sheet Polymers Testing and Development	4	Academic	$5–$10	6	5	5	12	
			4	1	1	6		

SOMMAIRE

Le principal objectif de l'étude sur l'innovation pour un transport ferroviaire propre menée par le Consortium de recherche et d'innovation en transport urbain au Canada (CRITUC) pour Transports Canada est de cerner les 10 secteurs technologiques les plus réalistes pour renforcer le futur réseau de transport de passagers et de marchandises au Canada. L'objectif global est de mener un examen préliminaire de l'état de l'industrie au Canada aujourd'hui, tant pour le transport des passagers que des marchandises, en termes d'innovations technologiques que Transports Canada pourrait utiliser pour orienter ses efforts à moyen et à long terme dans le domaine de la recherche, du développement et du déploiement. Comme élément fondamental de cette initiative, le CRITUC a intégré à ses secteurs du transport ferroviaire et de la mobilité des constructeurs et fournisseurs situés au Canada aux cinq séances de discussion nationales menées tout au long de 2018 et de 2019.

Au cours de ces séances, le CRITUC a consulté plus de 220 participants représentant une douzaine de compagnies et d'organisations dans le secteur ferroviaire, y compris des chercheurs universitaires, des exploitants ferroviaires, des constructeurs ferroviaires, des experts d'industrie et des fonctionnaires. Ces séances ont permis de cerner les grands thèmes technologiques dans le domaine de l'innovation ferroviaire : d'autres moyens de propulsion, l'efficacité énergétique, l'optimisation opérationnelle et les matériaux de remplacement.

Dans le cadre de cette initiative, deux séances de groupes de discussion portant sur d'autres moyens de propulsion ont eu lieu à l'Université Queens de Kingston (Ontario) le 22 novembre 2018, et au bureau de Metrolinx à Toronto (Ontario), le 11 février 2019. La séance du groupe de discussion portant sur l'efficacité énergétique a eu lieu dans le bureau de Ballard Power Systems, à Burnaby (Colombie-Britannique) le 10 avril 2019. La séance portant sur l'optimisation opérationnelle a eu lieu à l'Université de Waterloo (Ontario) le 3 juin 2019 et la séance sur les matériaux de rechange s'est déroulée dans les bureaux de Bombardier situés à Saint-Bruno (Québec), le 8 août 2019.

Le présent rapport contient une description détaillée de chaque domaine thématique technologique proposé au cours des cinq sessions de groupes de discussion, ainsi que les critères quantitatifs et qualitatifs qui ont permis de classer ces domaines thématiques selon une échelle de 1 à 10. Le rapport passe en revue la méthodologie, le processus de collecte de données, la méthodologie des groupes de discussion, l'analyse des données quantitatives et qualitatives et le résumé des résultats des séances des groupes de discussion ainsi que le classement qui en résulte. Des recommandations sont également formulées quant aux innovations potentielles dans le domaine du transport ferroviaire et de la mobilité, outre celles qui figurent sur la liste des 10 meilleures ou résultant des séances de discussion. Ces recommandations seront utiles pour la construction du futur réseau de transport de passagers et de marchandises du Canada.

Ce rapport comprend également une analyse documentaire des innovations à l'échelle mondiale dans le secteur ferroviaire qui montre que le Canada est à la traîne par rapport à plusieurs pays développés et en développement, en ce qui a trait à la conception, l'intégration, le lancement et l'essai d'autres modes de propulsion dans le secteur ferroviaire. Plusieurs éléments présentent un défi, notamment la commercialisation mondiale minimale des technologies innovantes, y compris l'utilisation de systèmes électriques à batterie sans caténaire et la propulsion électrique à hydrogène, bien que le Canada possède des ressources et une expertise technologiques de pointe dans ces domaines. Canada a toutefois le potentiel de prendre la tête de l'innovation dans le domaine du transport ferroviaire de passagers et de marchandises, étant donné la pollinisation croisée de

plusieurs grandes entreprises dans les secteurs des navettes, des autobus, des autocars, des camions et du rail pour l'électrification des systèmes de propulsion dans ce pays.

Pour établir le classement des 10 meilleurs projets d'innovation ferroviaire documentés dans ce rapport, le CRITUC a entrepris un processus de collecte de données en trois étapes. La première étape a consisté à identifier les principaux thèmes de recherche et d'innovation pertinents dans une perspective mondiale. Ces thèmes ont été extraits d'une analyse documentaire préliminaire et ont été communiqués à Transports Canada pour obtenir ses commentaires avant d'être finalisés. Pour la deuxième étape, une méthodologie de groupes de discussion semi-structurés a été utilisée pour développer les thèmes technologiques proposés. La troisième étape comprenait une analyse quantitative et qualitative des variables qui sont ressorties des séances des groupes de discussion, en utilisant une approche non pondérée pour dresser un tableau des quatre variables de base (soit, le coût, les délais, les progrès quant au niveau de maturité technologique (NMT) et le nombre d'intervenants) dans un classement quantitatif et le développement d'une méthode de codage thématique pour l'analyse qualitative.

Le tableau ES.1 montre les résultats du classement quantitatif intégrant les quatre variables quantitatives susmentionnées. Ces résultats quantitatifs suggèrent que la plupart des projets de propulsion alternative sont en tête du classement, alors que la plupart des projets de matériaux alternatifs sont classés plus bas. Dans l'analyse, CRITUC a également déterminé que le coût total d'un projet n'avait aucune incidence sur son classement. Si l'on ne tient pas compte du coût comme variable, les trois mêmes projets les mieux classés restent parmi les 10 premiers du classement général.

CRITUC a également défini cinq catégories d'analyse thématique qualitative, comprenant des variables économiques, environnementales, sociales, opérationnelles et technologiques, inspirées de la rétroaction des groupes de discussion. Ces résultats qualitatifs permettent de mieux comprendre les classements quantitatifs (soit les projets proposés ayant obtenu des notes de classement quantitatif similaires) et aideront Transports Canada à déterminer le statut socio-économique des participants des groupes thématiques technologiques spécifiques, et ce, tout au long du processus de consultation.

Il est important de noter que le rapport existant est une analyse préliminaire dont le but est de dresser un tableau du paysage canadien actuel dans le domaine de l'innovation technologique ferroviaire. Il faudra effectuer d'autres études détaillées et organiser des séances de groupes de discussion approfondies sur chaque thème de technologie pour dresser un tableau complet du potentiel d'innovations ferroviaires au Canada, et pour déterminer si les propositions d'investissement de haut niveau de l'industrie dans les domaines identifiés se concrétiseraient réellement si des leviers des pouvoirs publics concernés étaient mis en place pour soutenir une telle croissance.

Tableau ES.1. Classement quantitatif des projets ferroviaires. La note accordée à chaque variable est indiquée en rouge.

Projet nommé	Séance	Secteur	Coût (en million de $ CAD) /note	Niveau de maturité technologique /note	Nombre d'années /note	Nombre d'intervenants /note	Note totale	Classement du projet
Caténaires – electrification gratuite des installations ferroviaires	1B	Industrie	10 $ à 20 $	9	3	3		Premiers des 10 meilleurs
			6	10	7	10	33	
Passagers Hydrail	1B	Industrie/ Communauté	350 $	9	4	5		
			10	10	4	6	30	
Complémentarité entre GNC/hydrogène et le diesel	2	Universitaire	10 $ à 20 $	9	5	3		
			6	10	1	10	27	
Cours de triage Hydrail	1B	Industrie	250 000 $ à 50 M$	8	4	6		Milieu des 10 meilleurs
			8	7	4	4	23+	
Impression 3D de pièces ferroviaires de rechange	4	Industrie	5 $ à 10 $	9	5	4		
			4	10	1	8	23	
Intelligence artificielle pour la gestion du parc	2	Exploitants/ fabricants	5 $ à 10 $	8	5	3		
			4	7	1	10	22	
Démonstrateur de wagon	4	Industrie	50 $ à 100 $	7	6	5		
			10	4	1	6	21	
Outil de simulation des technologies de propulsion	2	Fabricants/ intégrateurs de technologie	3 $	6	1.5	6		Derniers des 10 meilleurs
			2	1	10	4	17	
Flux et capacité de la Gare Union de Toronto	3	Universitaires	1 $	6	3	5		
			2	1	7	6	16	
Électrification du transport ferroviaire	2	Gouvernement/secteur public	10 $	7	5	5		
			4	4	1	6	15	
Transport longue distance de marchandise avec Hydrail	1B	Gouvernement/universitaires	2 $ à 100 $	6	5	9		En dehors de la liste des 10 meilleurs
			10	1	1	2	14+	
Structure légère de Hydrail	4	Universitaires	10 $	6	5	4		
			4	1	1	8	14	
Sandwiched Sheet Polymers Testing and Development	4	Universitaires	5 $ à 10 $	6	5	5		
			4	1	1	6	12	

INTRODUCTION

Rail transport is crucial to Canada's transportation system. Canadian National Railway (CN) and Canadian Pacific Railway (CP) offer major freight rail operations in Canada, while passenger services are mainly provided by the federal crown corporation, Via Rail. Commuter-train services are also provided in three Canadian cities: in Greater Montréal by "Exo", or the Réseau de transport métropolitain, in Greater Toronto by GO Transit, a division of Metrolinx, and in Vancouver by West Coast Express. With more than 49,000 kilometres worth of tracks, Canada's rail transportation industry plays a critical role in promoting economic growth.

Rail research in Canada has been advanced through contributions from both academic and industrial institutions. Universities in Québec, Ontario, Manitoba, Alberta and British Columbia are actively conducting rail innovation research projects. These institutions mostly focus on rail infrastructure, operational optimization and climate change mitigation techniques. However, these research areas represent only a portion of the rail research conducted across Canada. Industries and the government have spearheaded efforts to reduce greenhouse gas (GHG) emissions from the transportation sector. Rail research in Canada has recently focused on alternative propulsion systems (e.g., hydrogen and catenary-free battery electric propulsion), energy efficiency, light-weighting and operational optimization. Since these research activities are dispersed across several Canadian academic institutions, efforts to coordinate and streamline university-led research are needed going forward.

The Innovation Centre of Transport Canada focuses on innovative research, development and deployment (RD&D) to support emerging transportation technologies, address disruptive technologies, and ensure that Canadians can access safe, secure and clean transportation systems. The Innovation Centre focuses on technological innovation to address emerging challenges such as the rapidly increasing flow of goods and people, increasing congestion, and the environmental footprint of transportation. It also facilitates Transport Canada to build collaborative initiatives with industry and academia to find common and applicable solutions to Canada's transportation challenges.

To identify core areas of technological investment and development critical to Canada's ongoing leadership in rail innovation, Transport Canada commissioned CUTRIC to survey industry and academic stakeholders to obtain insights into the most promising technology theme areas for rail innovation in Canada.

To achieve this goal, CUTRIC organized and moderated five focus group consultation sessions across the country to scan industrial and academic perspectives regarding promising rail technologies and Canadian expertise emanating from the following four areas:

1. Alternative propulsion (two sessions)
2. Energy efficiency
3. Operational optimization
4. Alternative materials

A wide range of academic researchers, rail operators, manufacturers, industry experts and government officials were integrated into the sessions, which were framed using both semi-structured and structured questions to support group inputs. CUTRIC used the outcomes of the consultation sessions to perform a quantitative analysis of the core variables (cost, timeline, technology-readiness-

level (TRL) advancement, and number of stakeholders) to generate a “Top 10” ranking of the most promising technologies for Canada to further explore in the future.

The results of CUTRIC’s consultation efforts are contained in this report, which is divided into three sections:

Section 1 provides a literature review of global innovative efforts allied to the four technology areas noted above.

Section 2 provides an overview of the focus group sessions and proposed technology theme areas, as well as the quantitative and qualitative methodologies used to provide project rankings and groupings.

Section 3 concludes with the summary of main outcomes from each focus group session and links the results of the quantitative and qualitative analyses to global rail innovation efforts. Important considerations as they relate to government, academia and industry sectors are provided in this section, as well.

SECTION 1: LITERATURE REVIEW OF GLOBAL RAIL RESEARCH AND INNOVATION

1.1 Alternative Propulsion

Alternative propulsion systems in railway vehicles involve powertrains that integrate drivetrain architecture without diesel propulsion. Such novel modes of propulsion reduce not only GHG emissions but also operating costs.

Within the global rail sector, non-renewable, hydrocarbon (diesel) fuel-powered rail systems are widely used today despite significantly contributing to global GHG emissions as well as air pollution in communities surrounding rail yards and access points for passengers using rail lines. A key factor that reinforces ongoing diesel-fuel reliance is the capital-intensive nature of rail system electrification. Typically, electrification is pursued only on heavy mainline railways with a high degree of track utilization [9]. The following literature review explores cases of alternative propulsion innovation arising in the rail sector (both freight and passenger rail) globally today. This situates Canada's challenges within a global context where these types of innovations are already occurring.

1.1.1 United States

In the United States, 87 per cent of the total energy used in rail is produced by diesel fuel [10]. Currently, the U.S. has less than one per cent of its tracks electrified which is a low number compared to many other countries [11]. Among the electrified tracks via catenary systems, Amtrak's Acela Express is the only high-speed rail (HSR) (Tier II) in North America [12].

One study involving alternate propulsion fuels, such as biodiesel, liquefied natural gas (LNG), compressed natural gas (CNG) and hydrogen (H2), was conducted to assess the cost effectiveness and emissions reduction potential associated with such fuels in passenger and freight rail applications. The study concluded there is no clear leader when considering both cost savings and GHG emissions reductions primarily due to significant uncertainty in the production and availability of these alternative fuels [13]. However, the study also concluded that it is crucial to encourage more public and private investment into research and development (R&D) of new technologies with more demonstrations and pilot projects to generate empirical outcomes [13].

In 2010 and 2011, a prototype of a hydrogen fuel cell powered switch engine was tested in the Los Angeles metro area in California by BNSF Railway. Ballard was the power system provider for the prototype switch engine [14] [15].

In Dallas and Detroit, battery powered street cars with folding pantographs on top of the vehicles were deployed in 2015 and 2017, respectively [16] [17]. These street cars use onboard batteries to power most of the route and use the pantograph to charge the battery on a small portion of the route.

In 2017, Florida East Coast Railway converted its entire locomotive[1] fleet to LNG [18]. Based on their claim, it takes about 90 minutes to refill an empty LNG tender, which is enough to power the train for

[1] "Locomotive" in this report refers to transport vehicles that run on rails and provide the motive power for trains. Locomotives may generate their power from different sources of energy and by virtue of different energy conversion mechanisms (e.g. fossil fuels converted through internal combustion engines or turbines, continuous

up to 1,450 kilometres under heavy haul service conditions, operating at a maximum speed of 97 kilometres per hour.

Currently, there are several states building or planning to build HSR systems using catenary wires. For example, California is currently building an HSR connecting San Francisco and Los Angeles with a designed speed of 350 kilometres per hour [19]. In 2018, Oregon, Washington State, Microsoft and British Columbia (Canada) dedicated approximately US$1.5 million to examine the business case for an HSR in the Pacific Northwest corridor [20]. In 2019, Texas started building an HSR between Dallas and Houston using Japan's HSR technology [21] [22]. Brightline, the only privately funded high-performance intercity railway service in the U.S., is planning to build an electrified HSR for passenger service between Las Vegas and Los Angeles in 2022 [23] [24] [25] [26].

With regards to more advanced technologies, Virgin Hyperloop One launched a working demonstration project operating in Nevada since 2018 and completed a feasibility study in October of the same year, which concluded the first passenger-bearing loop and will be ready by the mid-2020s [27]. Based on the design, the pods are being designed to travel over 1,000 kilometres per hour once completed.

1.1.2 Germany

In Europe, the length of the electrified network doubled over a span of 38 years between 1975 and 2013, reaching 61 per cent of the network [28]. In Germany, about 60 per cent of railway tracks were electrified by 2017 [29]. The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) has launched several locomotive shunting trials, which evaluate performance, reliability and lifetime costs of H2 locomotives. The FCH JU has stated that the European rail sector is strongly considering alternative propulsion systems [30]. In Germany, the French rail manufacturer, Alstom, has presented its latest zero-emissions train, Coradia iLint, on a test run demonstrating the potential of hydrogen fuel cells in passenger service trains. In early 2018, Alstom launched a passenger hydrail test run [31]. With two hydrogen rail prototypes already under construction and deployed as of 2018, Germany expects to have 40 fuel cell powered passenger train lines in operation by the end of 2020 [32].

In September 2018, Bombardier unveiled its new battery-operated train — its first to enter passenger operation in Europe in 60 years. A 12-month trial with passengers onboard had started in 2019 [33]. Since 2010, Bombardier has been developing its PRIMOVE technology for powering trains and electric buses wirelessly in Europe [34]. In 2012, Augsburg successfully completed the PRIMOVE light-rail tram trial test [35]. A main advantage of the PRIMOVE technology, compared with catenary technologies, is that it eliminates the need for overhead wires, which may be especially relevant for Canada, as electric wires may freeze in winter, blocking electricity transmission.

1.1.3 United Kingdom

In 2018, the United Kingdom (U.K.) outlined plans to remove diesel-only trains by 2040 [36]. In 2019, the U.K. began building a 193-kilometre HSR between London and Birmingham with an expected completion date of 2026 [21]. In hydrail, Alstom and a British rolling-stock operating company are collaborating to bring H2-powered trains to the U.K. as early as 2022 [37].

or battery-based electricity coverted through electric motors, or hydrogen fuel converted through hydrogen fuel cell stacks and electric motors, for example).

1.1.4 Ireland

Recently, Ireland's national railway operator, Iarnród Éireann, planned to add 600 electric and battery electric powered locomotives over a 10-year timeframe to replace its original fleet, which will be 45 years old by 2027. This is a €2 billion EUR investment under Project Ireland 2040 [38] [39].

1.1.5 Russia

Russia has a similar geography and climate to Canada, including vast land expanses with relatively small populations and cold weather in winter. Their experiences with alternative propulsion systems may be a useful resource for Canada to leverage. In 2002, Russia fully electrified the Trans-Siberian railway (about 9,000 kilometres) via catenary wires and used it to carry passengers and freight trains [40] [41]. In 2019, Russia started constructing a 762-kilometre HSR connecting Moscow and Kazan; Russian Railways with Chinese support are developing the line [21].

1.1.6 China

In 2017, 68.2 per cent of the total 127,000-kilometre railway in China had been electrified, ranking it the world leader in electric rail deployment [42]. These electrified railways can also be used for freight trains. In 2015, Sifang, a Chinese South Rail Corporation subsidiary, developed a hydrogen-powered train that can reach a maximum speed of 70 kilometres per hour and has a range of 100 kilometres. Further research in developing technologies to increase efficiency and improve cost effectiveness is currently underway [43]. In 2017, prior to the high-speed magnetic levitation (maglev) train-design launch, China completed a trial operation of its first driverless maglev passenger train in Beijing, reaching a maximum speed of 100 kilometres per hour [44] [45]. In addition, China recently completed a design for a maglev train that is capable of travelling at 600 kilometres per hour; a test-run is scheduled for 2020 [46].

1.1.7 Japan

The East Japan Railway Company has been involved in fuel cell system research for railcars for more than a decade. It announced plans to develop a fuel cell railcar as far back as 2006 [47]. Besides fuel cells, Japan has developed and tested its state-of-the-art maglev train, which reached a world record speed of 603 kilometres per hour in 2015 [48]. Currently, a 285.6-kilometre maglev line is under construction between Tokyo and Nagoya, and it is to be completed by 2027 [49]. The designed operating speed of the maglev line is 500 kilometres per hour.

1.1.8 South Korea

The Korea Railroad Research Institute is developing a hydrogen powered railway vehicle that has a range of 600 kilometres with a maximum speed of 110 kilometres per hour [50]. The expected test will be in 2022. Besides hydrail research, South Korea has been developing its HSR technology and building HSR lines [51]. Its HSR technology is competing with those being developed and deployed in both Japan and European countries in an effort to compete in the global HSR marketplace [51].

1.1.9 Other Countries

In 2018, Morocco completed the first HSR in Africa connecting Casablanca and Tangier [52] using catenary wires. The HSR is 323 kilometres long, and the operating speed is 320 kilometres per hour. In 2019, Egypt started constructing a 900-kilometre HSR line between Alexandria and Aswan [21]. In 2017, India started building its first HSR line using Japan's Shinkansen technologies [53]. The HSR line is 508 kilometres long with a designed operating speed of 340 kilometres per hour, scheduled for

completion by 2022. In 2018, the Indian government approved a proposal to electrify all Indian railways by 2021–2022 [54].

In 2019, Thailand commenced building a 983-kilometre HSR between Bangkok and Padang as part of its 2,506-kilometre HSR plan [21]. Sweden, Poland, Turkey and Denmark will also start constructing new HSRs in their respective countries [21].

1.1.10 Canada

In Canada, most trains are currently powered by diesel and diesel-electric propulsion systems and are not considered to be HSR. Freight services account for a significant percentage of total GHG rail emissions in Canada [55]. Some transit locomotives, such as those in TransLink's Skytrain in Vancouver, possess electrified motor and propulsion technologies. The Skytrain incorporates two of three rail lines powered by linear induction motor technology along with power rail systems [56]. TransLink's Skytrain is considered the longest automated light-rapid transit system in the world.
In freight rail, CN has previously demonstrated the use of an alternative fuel mix consisting of liquified natural gas (LNG) and diesel in a nine-to-one proportion to power two 3,000-horsepower trains between Edmonton and Fort McMurray from 2012 to 2013 [57]. However, after a second attempt in 2015, CN announced the need for more research and development (R&D) to render the project sustainable in economic terms [58]. Biofuels have been explored as alternative propulsion mechanisms in the freight sector, but adoption has been slow since raising biofuel levels could increase the risk of damage to the diesel engine. There is also uncertainty about expensive equipment [59].

In passenger rail, VIA Rail is currently considering a route upgrade along the Windsor-Quebec City corridor by converting it into a high-frequency rail service. The deployment of locomotives powered mainly by electricity with diesel-electric hybrid engines installed is one option that has been considered for this project [60].

Ontario is also exploring the possibility of transforming the face of the GO rail network from diesel dependency to electric-powered propulsion systems, as part of its effort to increase speed, frequency and efficiency of the Go rail network overall. As a first step toward electrifying GO-owned corridors, Metrolinx completed a Transit Project Assessment Process (TPAP) in 2017, which built on previous feasibility studies including the 2010 GO Transit Electrification Study [61], the Transit Project Assessment Process (TPAP) for the Union Pearson Express, and the Class Environment Assessment for Minor Transmission Facilities conducted by Hydro One [62]. In 2017, the Ontario Ministry of Transportation announced it was considering hydrogen fuel-cell technology as an alternative to overhead wires, as part of the electrification of GO transit [63]. Metrolinx then pursued a feasibility study investigating the potential of hydrogen fuel cells as an alternative propulsion strategy for GO rail services including the UP Express service to Pearson Airport [64]. In the same year, the Ontario government proposed an HSR to connect Toronto and Windsor using electrified locomotives [65].
In the spring of 2019, Infrastructure Ontario issued a Request for Proposal (RFP) for a massive GO Rail Expansion with most of it operating on electrified lines. This RFP shows that the Ontario government is continuing to advance the electrification plan of the GO rail network that took place during the previous government administration [66].

Most recently, Metrolinx has recognized that building an electrified integrated transit network requires a multi-year, multi-phase systems approach. An Addendum to the GO Rail Network Electrification Environmental Project Report (EPR) is now being completed to assess the full suite of electrification

infrastructure needed to support new tracks and layovers proposed as part of the new GO network, which were not previously assessed as part of the 2017 EPR [67]. Metrolinx plans to deploy electrified trains by 2025 through the GO Regional Express Rail (RER) program [64] [68].

Another passenger rail transportation innovation was announced recently by a start-up company, Magnovate Technologies, based in Edmonton. The purpose is to build a maglev train ferrying passengers around the Toronto Zoo [69] [70]. The maglev train is designed to run at 30 kilometres per hour in the zoo, based on an advanced climate-control system that optimizes energy utilization onboard the vehicle to provide year-round service to zoo visitors without catastrophic state-of-charge reductions within the battery system due to auxiliary heating loads [70].
Along with the U.S.-based Virgin Hyperloop One, a Canadian company, TransPod, is working to develop vacuum tube train (vactrain) technology. Founded in 2015, TransPod plans to begin building its first line by 2025 either in Canada or Europe, with operations starting in 2030 [71]. TransPod has also released the results of Hyperloop pre-feasibility study for Thailand in the spring of 2019, which proposes to offer significant improvements to Thailand's economy and the lives of its citizens [72].

Summary

In summary, several general conclusions can be drawn from the literature review with regards to alternative propulsion systems:

- Canada's adoption and implementation of alternative propulsion technologies (as well as HSR propulsion systems) is slower than most developed countries and some developing countries, such as Morocco and China.
- Many countries are building or planning to build HSRs, as they see HSR technology as a long-term solution for economic growth and GHG reductions.
- There is an opportunity for Canada to apply domestically developed rail technologies, such as hydrogen fuel cell technologies, wireless power transfer systems and battery train technologies along specific corridors that boast high-density passenger traffic.

1.2 Energy Efficiency

The term "energy efficiency" in transportation is generally described in relation to fuel consumption efficiency – i.e. the measure by which a system carries the same mass across a given travel distance.

Although rail is currently considered a highly efficient mode of transport from an energy perspective, there exists potential for improvement through further reductions in energy consumption and emissions [73]. For example, as discussed in previous sections, replacing diesel with electrified trains is a promising, practical and sustainable way to improve energy efficiency and reduce GHG emissions [74]. Electrified locomotives consume energy more efficiently when compared with non-electrified locomotives [74]. A recent study found that diesel and electrical drivetrains have similar total costs, and it depends on the track specifications if electrification is economically viable [75].

In this section, the focus is on R&D regarding other technologies for improving railway energy efficiencies and reducing GHG emissions such as improving power-system efficiency, integrating energy storage systems, converting diesel to diesel-electric hybrid modes, and improving train aerodynamics and railway operations.

1.2.1 Electric Power Systems

Many countries have been pursuing efforts to modernize railway electrification systems to improve energy efficiency and reduce power losses in the network [73]. Some European countries have seen upgrading legacy direct current (DC) systems as a method of improving energy efficiencies. The Netherlands, for instance, is considering converting its catenary system from 1.5-kV DC to 3-kV DC, as one study shows that a 3-kV system would allow almost 100 per cent energy recovery from regenerative braking compared with 50 per cent energy recovery using a 1.5-kV system [73]. In total, the analysis estimated a 20 per cent reduction in energy consumption annually using the 3-kV DC system; meanwhile, the 3-kV DC system can also improve train acceleration [73].

In France, as the current 6,000-kilometre 1.5-kV DC electrification systems are reaching end-of-life, the government is considering migrating to a medium voltage system, which allows 9-kV DC voltage [73]. A case study showed that by using such high voltages, the number of substations can be cut from six to two for a 100-kilometre track, and overhead wire cross-sectional areas can be reduced from 850 mm^2 to 266 mm^2, which could save €20 million on copper per 100 kilometres [73]. Energy consumption can also be reduced by six per cent, which is about 2 GWh of savings in electricity per 100 kilometres annually [73].

In addition to the voltage increase option, the French government is exploring the use of superconducting cable, which needs to be cooled to -19 degrees Celsius by liquid nitrogen. The benefit of using superconducting cable is that there is no heat generation or electromagnetic emission from the wire, resulting in operational cost reductions [73].

The Norwegian government has increased the voltage on its electrified railway system from 15-kV AC to 30-kV AC, reducing electricity transmission losses by 56 per cent, and increasing the distance between two converter stations from 80 kilometres to 120 kilometres [73]. On the Kiruna-Narvik line in Norway, trains loaded with iron ores running downhill generate a significant amount of electricity, making the line a net-electricity producer instead of a consumer [73].

In the academic research world, Youssef *et al.* designed and developed an efficient multilevel DC/AC traction converter for railway-electrification purposes [76]. The multilevel converter possesses a significantly lower component voltage stress compared with pulse-width modulated topologies, which reduces switching losses by achieving a zero-current switching operation without an auxiliary circuit. As a result, the system benefits from a 98.5 per cent operating efficiency at full load, which is higher than the previous 97 per cent efficiency achieved [76], leading to US$1 million savings over the lifespan of trains [76].

1.2.2 Energy Storage Systems (ESS)

Usually, it is challenging to harvest the energy generated from braking processes, as braking power differs from train to train, and the sequences of charging and discharging are unpredictable [73]. In many cases, the regenerated energy is simply consumed by the onboard resistor as heat [77] [78]. As technologies improve, such challenges can be solved. Usually, lithium-ion batteries, supercapacitors or flywheels are installed at the railway stations to store energy generated during the braking process for train-acceleration purposes [73].

Battery energy storage systems (ESSs) usually have high capital and operational costs [78]. Current lithium-ion batteries do not appropriately handle the repetitive short periods of charge and discharge cycles for subway operations, so oversized battery storage is usually used [78]. However, battery storage systems are applicable in cases of low frequency of charge and discharge cycles, with longer periods for each cycle [73]. Supercapacitor ESSs can properly handle rapid repetitive charge and discharge cycles, and they are generally maintenance free with long lifespans [73]. Hybrid ESSs with a battery and supercapacitor can present the best of both systems, thus, prolonging battery lifespans and improving energy efficiency [73].

When compared with battery and supercapacitor storage systems, flywheel technology also offers a compelling case as an ESS, because it demonstrates the most economical life-cycle cost. It is also more durable and reliable for stabilizing the system's voltage as it removes voltage vibrations during train acceleration and braking, which is crucial for protecting other equipment from damage [78]. Flywheel technology can charge and discharge in seconds for millions of cycles without affecting performance [78].

In 2016, the University of Alberta completed a study using a flywheel ESS for Edmonton's light-rail transit (LRT) and discovered that it can save operational energy up to 31 per cent with a cost savings as high as 11 per cent [79] [80]. In another study, trackside flywheel energy storage applied to DC light-rail networks shows potential to improve energy efficiency by 22.6 per cent in a multi-train analysis [81]. As for heavy haul locomotives, the flywheel energy storage system is more beneficial compared with batteries because of current battery limitations with regards to power, cost and service lifetime [82].

ABB has developed a roadside ESS to recover braking energy and increase energy efficiency using supercapacitors and batteries as storage media [83]. This storage system has been used in Poland's Warsaw Metro [84] [85].

In Canada, Ontario's Eglinton Crosstown LRT integrates ESS onto its line. The ESS can also be charged at night with low-cost electricity and used during the day, which saves operational costs and increases service reliability in case there is power shutdown from the grid [86] [87].

Aside from roadside ESS, in 2007 Bombardier conducted an experiment using onboard supercapacitors to reduce energy consumption for light-rail vehicles (LRVs), resulting in a 30 per cent energy reduction [88]. Other benefits of onboard supercapacitors are that they can significantly reduce on-peak power demand (up to 50 per cent) and allow catenary-free operation for a short period. In Japan, a similar study shows that 77 per cent of regenerated energy can be used effectively using the supercapacitor as onboard energy storage [89].

1.2.3 Diesel-Electric Hybrid

The concept of a "locomotive" has changed over time. Traditionally, it has referred to the rail vehicle that pulls a series of rail cars along, by providing motive power. It may be referred to as a "motor coach" or "power car", when it is used to carry a payload such as a series of other vehicles. Locomotives are self-propelled vehicles. They can be designed using various propulsion technology mechanisms including, diesel engines, natural gas turbines, hydrogen fuel cell stacks with batteries, and electric grid-connected continuous power systems or electric battery systems.

While it is the case that locomotives have historically "pulled" trains along, "push-pull" technology has become more common whereby a locomotive or locomotives may be located at the front, middle, rear or both ends of a vehicle in a distributed fashion. This is sometimes referred to as "distributed power" systems. Specifically, "electric" locomotives have been historically powered by catenary or otherwise conductive systems through a grid-connected power source that delivers continuous power. However, battery electric systems do exist in which the locomotive is powered by an onboard battery or hydrogen-electric fuel cell stack combined with a battery system. Within the spectrum of electrification, hybrid electrified systems have also emerged in ways that have meaningfully innovated the energy efficiency characteristics of diesel-powered locomotives.

Traditional diesel locomotives use a mechanical braking mechanism that wastes kinetic energy as heat. A recent study that compared the fuel-efficiency performance of conventional and hybridized locomotive models found that battery hybrid locomotives can significantly reduce fuel costs, amounting to a 16.5 per cent cost reduction and proportional GHG emissions reductions by harvesting usually wasted braking energy through regenerative braking [90]. Diesel-electric hybrid systems with onboard ESS-supported locomotives can harvest kinetic energy during the braking process and reuse it during the acceleration process to reduce energy usage [74]. This type of train is especially beneficial for routes with many stops.

In 2017, Hoffman *et al.* developed an innovative diesel-electric hybrid drive system for rail cars, claiming a fuel savings of up to 32 per cent from simulation results [91]. Also, in recent years, major locomotive manufacturers such as Alstom, Siemens and General Electric have developed variants of diesel-electric hybrid locomotives to improve fuel efficiency [92] [93] [94].

At the 2016 InnoTrans Conference, German Rail [Deutsche Bahn (DB)], Toshiba and Henschel announced a plan to convert over 300 diesel-hydraulic locomotives built in the 1970s to diesel-battery hybrid configurations, which is predicted to extend the working lives of these locomotives by 16 to 20 years and reduce diesel-fuel consumption by approximately 20 per cent [95].
In 2015, Spiryagin *et al.* studied an onboard flywheel ESS with a simplified control strategy for heavy-haul diesel-electric locomotives [82], which showed a saving of 16.65 per cent in diesel-fuel consumption [82].

1.2.4 Aerodynamics

Reducing aerodynamic drag offers another opportunity for improving rail energy efficiency, especially for HSR. When a train reaches speeds of 205 to 300 kilometres per hour, the aerodynamic drag force can account for 75 per cent of the total energy consumption [96]. Ding *et al.* wrote a research paper about aerodynamic design principles for HSR in detail [97]. The aerodynamic design method has helped China in developing various kinds of high-speed trains to achieve different goals [97]. However, as aerodynamic design problems are often complicated, the authors expressed that extensive research in this area is still needed.

Recently, CRRC Group (China) has been studying how to reduce the aerodynamic drag force for high-speed trains by working on different areas of the train, such as the pantograph and surface [98] [99]. For example, just as the microstructure on shark skin reduces liquid drag force, microstructures added to the nose surface of high-speed trains can do the same, as demonstrated in a collaborative research project between Southwest Jiaotong University and the CRRC. Adding such microstructures reduces aerodynamic drag force, though minimally [99]. On low- to medium-speed metro systems, both the CRRC and South Korean University found that compared with a blunt-shaped nose, a streamlined nose can reduce aerodynamic drag by up to 50 per cent at speeds greater than 100 kilometres per hour [1] [100]. Figure 1 demonstrates the difference between the streamlined and blunt design of the metro train. In addition, increasing the cross-sectional area of the tunnel can reduce up to 50 per cent of the aerodynamic drag as well [100].

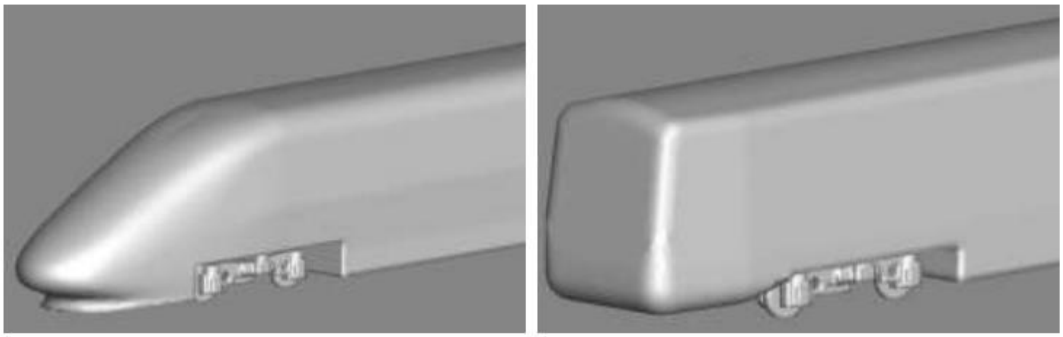

Figure 1.
Streamlined versus blunt design of metro train [1]. Figure reprinted from 2nd International Conference on Industrial Aerodynamics (ICIA 2017) 2017. Lancaster, PA: DEStech Publications, Inc.

In freight rail, 80 per cent of total drag is still from aerodynamic drag at 115 kilometres per hour, according to a study by Li *et al.* [2]. In this study, researchers found the greatest drag reduction for freight trains occurs when the gaps between containers are smaller than 1.77 metres in cases where one container wagon is one metre wide [2]. In instances where gaps are unavoidable, it is preferable to have a single large gap as opposed to many medium-sized gaps [2], as illustrated in Figure 2.

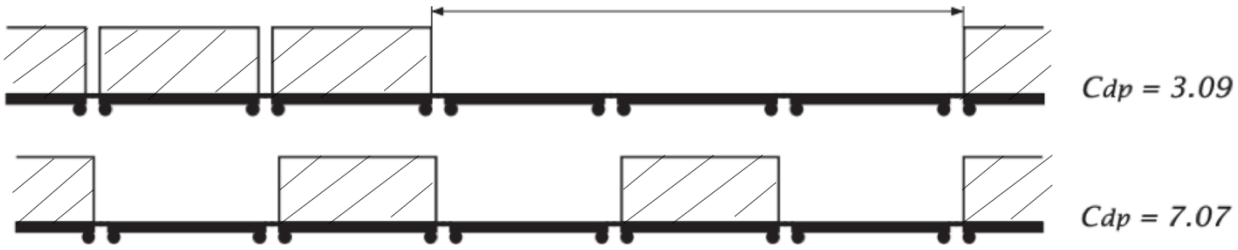

Figure 2.
One big gap between containers generates less air drag than many medium-sized gaps [2]. Reprinted from Journal of Wind Engineering & Industrial Aerodynamics Volume 169, Li et al., Flow topology of a container train wagon subjected to varying local loading configurations, 12-29, Copyright (2017), with permission from Elsevier.

In a 2011 study, researchers found that aerodynamic drag consumed about 15 per cent of the total energy to propel a coal train and was almost the same for both empty and full trains [101]. Researchers also explained that using simple fairings or foils to direct air flow can reduce air drag by approximately 25 per cent and fuel usage by approximately five per cent [101].

1.2.5 Operational Improvement

Even if kinetic energy is being recycled in regenerative braking, braking and accelerating processes still require large quantities of input energy, as regenerative processes are not 100 per cent efficient. Avoiding unnecessary braking therefore presents an immediate opportunity for improving energy efficiency.

Thales has developed the SalTrac® Green Communications-Based Train Control (CBTC) 2.0 technology, adopted by London Underground Ltd., to reduce energy and improve efficiency in this manner [102] [103]. The Green CBTC system reduces energy consumption in the following ways:

- Calculating optimal cost strategies in between stations.
- Generating real-time reactions to disturbances to avoid unnecessary energy expenditures, such as unnecessary braking and acceleration.
- Managing available regenerative energy.

Thales has reported the Green CBTC technology grows a system's energy planning capabilities and helps to achieve an average of 40 per cent energy savings by increasing travel time by only seven per cent.

Big data and artificial intelligence (AI) technologies are also becoming increasingly popular options for optimizing various processes in the rail industry to improve railway operations, safety and maintenance [104] [105] [106]. Big-data analytics in rail transportation can identify bottlenecks, maximum loads, variations in traffic, unplanned delays, inspection timings, etc. [105]. Big data can thus enhance the overall efficiency and reduce energy consumption and operating costs of a rail network or fleet [105].

Li *et al.* from IBM and the State University of New York developed a machine learning method to predict impending failures and alarms for critical railcar components by letting the machine "learn" from historical sensor measurements [107]. Based on the study, AI applied to rail-optimization efforts achieved significant gains in railway safety, resulting in higher rail network velocity [107]. This indirectly reduces energy usage for rail networks by reducing the number of derailments and other accidents. This technique is specifically useful for Canada, as Canada has a vast rail network across which this technology can reduce labour resource requirements.

Jamshidi *et al.* also developed an AI methodology for assessing the risk of rail failures. This method analyzes images taken from video cameras along the railway so that maintenance staff can take action at the right location and time to prevent accidents [108].

Summary

In summary, several general conclusions can be drawn from literature with regards to energy efficiency in rail operations:

- Many countries have been pursuing efforts to modernize railway electrification systems to improve energy efficiency and reduce power losses in the network.
- Electric power systems, ESSs, diesel-electric hybrid systems, aerodynamics and operational improvements are proven methods to increase energy efficiency within the rail sector.
- There is an opportunity for Canada to apply highly developed rail technologies, especially within ESSs, to boost energy efficiency across the rail sector.

1.3 Operational Optimization

Operational optimization can help to improve energy efficiency and reduce GHG emissions, as optimized operations not only reduce unplanned delays and stops but also improve customer satisfaction, attracting more riders and users to the system. To further optimize rail operations, improvement considerations in the rail sector should be viewed with other modes of transportation, such as buses, bicycles, autonomous vehicles, etc., as a healthy transportation ecosystem requires a well-planned and smoothly connected transportation system across all modes. This not only improves energy efficiency in the rail industry, by moving more people across the same distance with less energy expended per passenger, but it also improves the entire transportation system's overall efficiency. This section reviews technologies and research associated with railway operations optimization efforts and integrated mobility outcomes.

1.3.1 Railway Scheduling

CUTRIC's research reveals numerous academic research activities worldwide that focus on optimizing railway scheduling. However, it is difficult to identify publicly available outcomes associated with R&D in this area from within the rail industry. This may be due to proprietary restraints on commercially available information or a lack of industry investment and implementation experience in this space. These phenomena are identified in an overview paper by European researchers Cacchiani *et al.* [109], which contends, "The development of algorithmic real-time railway rescheduling methods is currently still mainly an academic field, where the research is still far ahead of what has been implemented in practice." Unfortunately, the railway industry has never been a quick adopter of newly available and innovative methods and concepts." As a result, there is large potential for improving a railway's scheduling system to reduce delays and energy usage in Canada if the rail industry adopts academically investigated innovative techniques.

In general, railway tracks across Canada are shared in between passenger rail and freight rail vehicles. Because passenger and freight railways operate at different speeds, it is important to optimize schedules between passenger and freight rail to avoid unplanned stops and slowdown on tracks, which cause delays and lead to unnecessarily high energy consumption by the rail system. Currently in Canada, it is not uncommon for passenger rail to experience delays due to traffic congestion between passenger and freight rail [110] [111]. As Canada's population has grown rapidly in the Greater Toronto Area (GTA) in recent years [112] and is expected to continue growing similarly [113], there will be increasing demands for both freight and passenger rail services in the area. Consequently, rail operations that are not optimized to meet higher demands may experience increased delays and congestion on the railroads into the near and long-term future; thus, an opportunity exists for the Canadian rail system to invest in better railway control systems to optimize rail operations.

In academia, many researchers have developed models and simulations to optimize railway scheduling to address this issue [109]. Wang and Goverde developed a multi-train trajectory-optimization tool that improves energy efficiency and reduces delay recovery times on single-track railway lines which can be used for both passenger and freight applications [114]. German

researchers have developed optimization strategies for long-term freight-train routing, mid-term rolling stock rotation planning and train dispatching for passenger train schedules, because passenger trains have fixed timetables and are more sensitive to delays [115]. For the same reason, Swiss scholars have developed a feed-forward simulation tool to optimize freight rail speed profiles and minor rescheduling actions by considering stop avoidance, itinerary changes and early departures. The model demonstrates reduced energy consumption by up to 12 per cent in the Swiss railway case [116].

Most literature on railway-disruption management focuses on rescheduling one variable, such as timetable, rolling stock, or crew. However, Dollevoet *et al.* shows an iterative framework considering all three variables [117]. The framework has been tested in several disruption scenarios on Netherland's railways, demonstrating that railway operators can develop a new timetable, rolling stock and crew schedules quickly during disruptions, such as track blockages [117].

Beside railway scheduling optimization, accurate predictions of train delays can improve operations by allowing train operators to take preventative actions to avoid or relieve further delays [118]. Italian researchers, Oneto *et al*., have developed a machine-learning algorithm to dynamically predict train delays for large-scale railway networks in Italy [118]. This algorithm can extract useful information from a large amount of historical operational data and weather data. The results show this method is twice as robust as current state-of-the-art methodologies [118]. In future work, more external data will be added into the system to improve accuracy, such as passenger-flow information.

Though optimizing a railway system can help to improve railway operations, there is still an upper limit on the capacity of railway tracks [6]. A rail system's speed and operation can still suffer once the number of trains reaches the capacity of the railway tracks.

Table 1 shows the study's results for a railway corridor's capacity using different control systems [6], demonstrating that building extra or separate tracks is necessary before the number of trains reaches the capacity of rail corridors.

Table 1.
Average capacities of typical rail-freight corridor trains per day [6].

Number of tracks	Type of control	Trains per day	
		Practical maximum if multiple train types use corridor*	**Practical maximum if single train type uses corridor****
1	N/S or TWC	16	20
1	ABS	18	25
2	N/S or TWC	28	35
1	CTC or TCS	30	48
2	ABS	53	80
2	CTC or TCS	75	100
3	CTC or TCS	133	163
4	CTC or TCS	173	230

Legend: N/S or TWC – no signal/track warrant control
ABS – automatic block signalling
CTC or TCS – centralized traffic control/traffic control system

Notes:
** For example, a mix of merchandise, intermodal and passenger trains*
*** For example, all internodal trains*

With increasing populations across Canada, especially in the Greater Toronto Area (GTA) expected over coming years [112] [113], freight and passenger trains will increasingly suffer from congestion related delays; thus, building extra tracks in advance may be reasonable for long-term rail-systems planning.

As shown in a previous section of this report, many countries have developed dedicated HSR tracks for passenger trains. In Canada, past proposals from industry and passenger rail advocates have included building a dedicated track for passenger rail to separate it from freight rail operations, as sharing tracks has already hindered both rail industries [119]. A dedicated railway track for passenger trains would likely increase train speeds, increase the frequency of trains, and reduce delays [119]. Dedicated tracks are also expected to reduce road congestion in major cities by 11 per cent [120]. Some application examples previously recommended in the literature include the following:

- UP Express, which runs on its own dedicated track and provides reliable, predictable and high-frequency services [121].
- GO Train services, as Metrolinx is planning to build new tracks to enable more frequent passenger train services [122].

1.3.2 Railway Maintenance

Though railway maintenance is not directly related to operational optimization, effective optimization can help to detect problems faster, greatly reducing the number of accidents and delays and indirectly improving a railway network's overall operational efficiency. A broken-down train blocking the track is a serious issue that can cause financial losses for the rail operator and economic costs to the jurisdiction, affecting both passenger and freight rail commercial viability [123] [124]. When such delays occur during weekday rush hours, broken or stalled trains can delay hundreds of thousands of passengers and tens to hundreds of employers across the network [123].

To improve the quality and efficiency of railway maintenance, railways need to continue to shift away from a methodology of "find-and-fix" to "measure-and-predict," which should allow maintenance to be carried out with minimum impact on traffic [125]. The good news is that there have been many research activities in recent years that use big data and machine-learning algorithms to detect equipment failures faster and more accurately, using large amounts of already available data collected by railroads' new-generation inspection and monitoring systems [7].

Recently, one study demonstrated the benefits of using a logistic regression model on curve management at the annual Big Data in Railroad Maintenance Planning conference hosted by University of Delaware [7]. Table 2 shows the study's comparison between conventional methods and the big-data method [7].

Table 2.
Benefits of big data on curve-condition management [7].

Conventional methods		Smart Analyzer + GeoDrive	
Manual surveying	10 months Team of four on live track	Detected 1,560 curves automatically	Few computing hours
Track outage	900 hours	No service disruption	Existing big data
Individual mistakes	Levelboard + stringline + human error	Numerical solvers	Geometry car
Slow	Annually (months)	8,000 curve points in hours	Weekly
No feedback	One-year turnaround	Direct communication	Immediate broadcast

In 2005, Yang and Létourneau from the National Research Council of Canada published a study using machine-learning algorithms to predict wheel failures [126]. To improve the performance of the method, researchers combined base-level models and classifiers to form a multiple classifier system, which can predict 97 per cent of wheel failures and maintain a reasonable false "positive" rate at eight per cent.
Similarly, Li *et al*. from IBM and the State University of New York developed a machine-learning method (support vector machine) to predict impending failures and alarms for critical railcar components by letting the machine "learn" from historical data, including failure data, maintenance action data, inspection schedule data, train type data and weather data [107]. Based on the study, the proposed machine-learning method can deliver 97 per cent precision for both train data and testing data, which could help rail operators achieve higher rail-network velocity [107].

Jamshidi *et al.* developed a method known as "deep convolutional neural networks" to assess the risk of rail failure by analyzing big data from ultrasonic measurements and images taken from video cameras along the railway, so that preventative actions can be taken at the right time and right place [108].

To reduce human error caused by vision fatigue in examination, Chinese scholars developed an automatic defect detection tool for fasteners on catenary supported devices using the deep convolutional neural network method [127]. This machine-learning algorithm can process digital images of the fasteners efficiently with a mean average precision of over 90 per cent [127]. The results suggest more research can be done to detect more component problems on the catenary device.

In the U.K., British railways have a strong interest in data-driven safety solutions [128]. Several research projects across the U.K. have provided insight into the current need for a transformation to big data applications in the ongoing and effective risk management of rail networks [128].
CN Rail recently demonstrated its newly automated inspection portals using an AI algorithm to examine trains [129]. The new equipment is 120 times more efficient than a worker to check a single car. In addition, trains do not need to slow down for the inspection, which improves railway efficiency. At the same time, CN showed its autonomous track-inspection car that uses laser and LIDAR technology to detect broken ties and defects on the track [129]. As the track-inspection car can be attached to a regular train and work at regular train speeds, there is no need to reduce train speeds, which is commonly done when manually inspecting tracks. Without slowing down trains, railway

operations can be improved significantly. According to CN, four automated portals in Winnipeg and one north of Toronto have already been installed, with more automated equipment expected to be added to reduce costs and improve efficiency [129]. CN executives highlighted that this initiative is not about replacing the workers who are fixing defects but rather spotting the defects and ultimately improving safety [129].

Based on the review of the literature in this area, it is tremendously beneficial to the Canadian rail industry to apply big data technologies to predictive mechanisms aimed at identifying railway defects and failures, given that Canada possesses a large railway network with a small population which can be difficult to maintain using human labour alone.

1.3.3 Real-Time Operations

Real-time operation can also be optimized to reduce energy usage. As with driving a car or any vehicle, differing driving strategies will cause different energy usage patterns [130]. For an automated system such as subways, an optimized coasting and braking strategy can save substantial energy for rail operators [131] [132] through reducing unnecessary braking and acceleration processes.

Sanchis and Zuriaga developed a computer model for optimizing metro-train speed profiles between two stations to minimize energy consumption [132]. By comparing actual metro-train energy consumption in Spain, the optimized simulation results demonstrate a 16 to 26 per cent energy reduction, depending on track conditions [132].

Zhang *et al*. developed a model to optimize high-speed train controls to achieve energy efficient operations with a slight adjustment of the timetable (average of 67 seconds) [8]. The simulation results show 7.6 per cent in energy savings by applying the new model compared with the actual energy-consumption data [8]. Table 3 shows other scholars' research on this topic [8].

Table 3.
Other research on optimizing rail operations [8].

Publication	Type of train	Energy savings (percentage)
Su *et al.* [133]	Metro	14.5
Yang *et al.* [134]	Metro	9.94–10.66
Cucala *et al.* [135]	High-speed	5.25–6.67
Binder and Albrecht [136]	Regional	4.3–12.9

Thales has developed the SalTrac® Green CBTC 2.0 technology, adopted by London Underground Ltd., to reduce energy consumption and improve efficiency [102] [103]. This is also mentioned in the previous section.

CN has been using a Trip Optimizer to regulate trains speeds and improve fuel efficiency by controlling the locomotive throttle and dynamic brakes. By the end of 2016, almost 490 GE Evolution Series locomotives were equipped with the Trip Optimizer [137]. In addition, CN has developed an in-house tool, the Horsepower Tonnage Analyzer, to optimize a locomotive's horsepower-to-tonnage ratio using data collected from the train to ensure no extra horsepower is wasted during a trip [137].

1.3.4 Integrated Mobility

Integrated mobility is a burgeoning topic in transportation innovation worldwide [138], and it is fundamentally dependent upon rail transportation as a mode of mobility. Integrated mobility provides passengers multiple ways to be transported seamlessly to their destinations. This seamlessness may rely on connections between different modes of transportation systems, such as rail, bus, bicycle, autonomous cars, etc.

An important aspect of integrated mobility is a unified fare system [138], which allows passengers to pay once for their journey instead of at every transfer point, such as from bus to train. Hong Kong has long offered the Octopus fare card that allows passengers to board from transit to ferries, and can be bought at retail stores [138]. In Canada, the Presto Card has been integrating different transit systems throughout the Greater Toronto and Hamilton Area (GTHA); however, the integration has been challenging as some transit systems do not collect adequately refined data from the card services. In general, fare integrated systems can increase ridership by expanding to include subways, buses, light-rail systems, inter-city passenger rails, coach bus services, and mobility-as-a-service (MaaS) vendors, etc. and use these systems to offer riders incentives to use multiple modes of travel rather than single-occupied cars from point to point. A seamlessly integrated mobility system would support, for instance, passengers using one digital fare card for bus, train, bicycles and car shares. It would also ensure optimized scheduling across the network so that a passenger exiting a GO Train would wait no more than a few minutes for a local bus or shuttle to arrive to ferry her final destination.

As an example of the importance of integrated mobility, consider the struggle Metrolinx has experienced with accessibility for the GO Transit stations across the GTHA. Due to inaccessibility, 75 per cent of people who use the GO Train network still opt to drive to the station rather than use a local service, and 85 per cent of station parking lots are at or near capacity on a daily basis [139] [140]. Additionally, the number of GO Train users has been increasing rapidly over the past few years [140], and as Metrolinx has pointed out, adding parking lots around GO Train stations is not a sustainable long-term solution economically, environmentally or from a land-use perspective [140]. A study in 2003 previously pointed to the same conclusion: any additional road capacity would be consumed quickly by newly generated traffic, also known as “induced traffic” [141]. To tackle the problem, Metrolinx has developed specific guidelines to optimize the use of its rail network and reduce vehicular travel to rail hubs:

- Walking: establish a network of safe, comfortable and well-maintained pedestrian routes around stations.
- Transit: coordinate with local and regional transit services to offer integrated schedules and fare-collection systems.
- Cycling: create safe bicycle lanes to stations.

Integrated mobility is in its early stages in Canada. There are still many areas that need to be addressed and targeted to create a truly integrated, seamless and sustainable transportation system. Achieving this goal will require different stakeholders across transportation services to cooperate to ensure short- and long-term success [142]. However, many factors, such as the diverging interests of stakeholders and incongruities across political jurisdictions that would need to be reconciled to achieve full integration of mobility services, may limit the formation of such alliances in the near to medium-term future.

Summary

In summary, there are several general conclusions to draw from the literature review regarding operational optimization and integrated mobility:

- There are many academic research activities on optimizing track usage, timetables and real-time train controls, but some areas within Canada's rail industry need improvement to become competitive globally. Specifically, the adoption of train scheduling systems that optimize the use of track for both freight and passenger rail is not advanced in Canada. However, rail operators have been employing data collection and telemetry tools to optimize the deployment and speeds of their own trains.
- As the GTHA's population is growing rapidly, separate tracks for passenger rail services may be an inevitable necessity in the long term given the current track's capacity limitations, even with advanced optimization systems.
- Numerous benefits arise when implementing big data technologies in rail maintenance to improve rail operations indirectly by reducing train breakdowns and other accidents. Canadian railway companies have projects underway to test and refine the ability to use big data to improve the capabilities of automated track and rolling stock defect detection equipment.
- Research and development in integrated mobility is important in increasing rail ridership and improving the energy efficiency of the entire Canadian passenger rail network.

1.4 Alternative Materials

Recent reports have shown that composites are becoming more prevalent in the rail industry in all countries; however, Canada is slow to adopt these changes [143]. Though rail is a highly efficient form of transportation, many opportunities exist to further improve energy efficiency. To address growing climate concerns, it is necessary to compound every measure to reduce GHG emissions and non-renewable fuel consumption. Generally speaking, reducing the weight of any vehicle by 10 per cent can increase relative energy savings by as much as five to eight per cent in standard passenger rail vehicles that regularly travel shorter distances [144] [145].
Additionally, structural weight reduction can lead to cost savings. A study in Singapore by Hofer *et al.* showed that based on current technology estimates, the light-weighting of both battery and conventional electric passenger car structures can increase net cost savings by at least 22 per cent and potentially up to 39 per cent [146]. For these reasons, weight-reduction techniques in rail can assist in reducing the industry's carbon footprint while improving its energy and economic efficiency. This section will focus on research pertaining to developing materials and design techniques used to reduce vehicle weight, while increasing structural strength and fulfilling other multifunctional benefits, such as noise reduction. The emerging field of additive manufacturing and its applications for fulfilling such design metrics will also be examined. Finally, the development of new materials for applications in rail ties for increased longevity and durability will be investigated.

1.4.1 Light-weight, High-Strength and Multifunctional Materials

Light-weight materials are extensively sought after in virtually every vehicular design industry, from aerospace to automotive. Because of the highly competitive nature of these industries, companies may seek out new materials in their designs to support weight reductions and to offer other multifunctional benefits, such as higher strength properties with less mass, or fire retardant properties. The benefits of alternative materials depend upon their intended specific application.

This section of the literature review provides a broad overview of such materials and their applications in rail.

Several global commercial examples can provide insight into this sector. The U.K.-based TRB Light-Weight Structures has designed interior rail car components, such as bicycles racks, toilet modules, storage units and catering carts, by implementing light-weight and multifunctional materials for Japan's Hitachi Rail and Italy's Pendolino [147]. Additionally, TRB Light-Weight Structures has manufactured doors and detrainment systems comprised of bio-composite materials for a large majority of U.K. rolling stock, leading to a potential 35 per cent weight reduction, as compared with competing components [147]. Another company, Saertex Group, has designed a coated fibre-reinforced plastic (FRP) fabric, which is 40 per cent lighter than aluminum with an active fire-retardant layer comprised of materials that produce non-toxic gasses when burned [148]. Getzner GmbH has developed a light-weight floating floor for use in passenger rail using a new Sylomer aluminum assembly, which simultaneously absorbs vibrations while reducing the overall structural weight, demonstrating that it is possible to improve current designs in tandem with economizing mass [149]. In 2015, academic researchers in South Korea even produced a glass-fibre reinforced polymer (GFRP) bogie frame that had a natural frequency 27.7 per cent that of its steel competitor [150] [151].

A common sub-theme in light-weight materials for rail applications is sandwich composites, which are commonly used in the flooring and walls of passenger cars, primarily due to their high strength-to-weight ratios. A series of studies carried out by Wennberg *et al.* at the KTH Royal Institute of Technology in Sweden in partnership with Bombardier, Saab Automobile AB and A2 Zound revealed that honeycomb sandwich composites used for flooring and walls in a newly designed passenger car can cause net-weight savings as high as 40 per cent compared with a benchmark passenger car [3] [4] [5]. TRB Light-weight Structures has also successfully implemented such materials in their own projects [147]. Sandwich panels have demonstrated other benefits such as improved crashworthiness, dynamic loading resistance [152] [153], acoustic damping for increased sound insulation [154], and thermal insulation and resistance to UV radiation and chemicals [155].

Other light-weight materials have found their way into the rail industry. Shift2Rail, a large-scale European initiative that aims to facilitate the improvement and evolution of different types of rolling stock for railway passenger and freight across the European Union (EU), launched REFRESCO, a 30-month long project that ended in 2016. The programme ended with laying the foundation for implementing regulatory procedures, testing and evaluation methods, and potential material candidates for use in rolling stock across the continent [156] [157] [158]. It is clear that the EU has been following in the footsteps of this initiative, as recently the German-based Fraunhofer Institute demonstrated its research for light-weight polyurethane composite panel engine housing for rail applications, causing a potential 35 per cent weight reduction compared with traditional steel counterparts [159].

A further example of combining several light-weight materials is demonstrated in the South Korean TTX, employing carbon epoxy and aluminum honeycomb sandwich composites. The train has demonstrated structural weight reductions of 28 per cent while complying with crash-safety standards [160], loading requirements, fatigue requirements and fire-safety standards [161].

In China, CRRC Qingdao has recently unveiled its new subway railcar system, which has been made 13 per cent lighter than traditional subway cars by employing cutting-edge carbon fibre technology. In addition to being lighter, the company has also employed a silicon carbide inverter and permanent magnet synchronous motor to reduce the train's energy consumption by 15 per cent [162].

Developments in friction stir welding has allowed for the use of magnesium alloys in rail cars as well. A study from South Korea has shown that using these alloys can potentially reduce the weight of a railcar by as much as two per cent [163]. Using magnesium alloys could be an effective solution, as it will require less of an overhaul in manufacturing processes than composites. Recently, this has been tested in Canadian research laboratories and outcomes were presented at the Alternative Materials Session of CUTRIC's Rail Innovation Focus Group [164].

In addition to using light-weight materials, it is also often economically and environmentally advantageous to use recyclable materials. In a recent report, Alstom declared its commitment to improving their rail cars for sustainable design for their Coradia Polyvalent trains across Germany. The report detailed many challenges the company must overcome to produce such a train, as well as potential solutions. One of these solutions is implementing alternative light-weight, multifunctional and recyclable materials for the car structure, which allows for a 93 per cent recyclability of the train upon unit retirement [165].

In Canada, research teams at the Polytechnique Montréal have experimented with high-performance thermoplastic composites for the railway industry using a reinforcement composed of a braided carbon-fibre yarn encased in a thermoplastic matrix [166].

Based on the literature review so far, it appears there is a strong appeal both in the academic and industrial sectors for the development of light-weight materials in the rail industry, and for the most part, the EU leads innovation in this capacity. Due to the vast physical distances between Canadian cities, Canada could greatly benefit from pursuing alternative materials research for rail applications specifically to generate cost and energy savings for rail cars and to keep pace with the increasing viability of innovatively designed rolling stock worldwide.

1.4.2 Railcar Structure Redesign

In applying alternative materials, it is often necessary to redesign the structure of a rail car because implementing different materials will inevitably alter the static and dynamic responses of the original design. Usually, this is done by carrying out structural optimization, often by means of a multifunctional, multidisciplinary design optimization (MDO) approach. The objective of an MDO is to reprioritize the structure such that areas that are more critical in terms of design objectives are given the greatest focus at a higher cost while less critical areas compensate for increased cost elsewhere. MDO is most commonly used for redesigning specific parts; however, it can also be used for the wholesale redesign of a large-scale structure [167].

An example of a simple, multi-step process of rail car structure redesign is demonstrated by Harte *et al.* [168]. In this study, a generic LRV is redesigned by optimizing the shape of the structure first such that the mass is minimized; at the same time, the stress is limited so that it does not fail. Next, the thicknesses across various portions of the car are optimized according to the same criteria. The results produce a rail car section that has dropped from 129.7 to 112.4 kilograms using an optimization algorithm and without drastically changing the manufacturing process [168].

Bombardier has recognized that implementing advanced materials without optimizing geometry can be very costly because composites are more expensive compared with aluminum or steel. As such, they have implemented a multi-step process to design passenger railcar structures [169].

A multi-objective approach can also be used, thereby allowing for the optimization of different design characteristics. In 2018, a Chinese team of researchers performed a multi-objective design optimization to reduce the weight of the underframe structure of a high-speed train, causing a net weight reduction of 13.06 per cent while enabling higher energy absorption and increased strength [170].

A multi-scale design technique optimizes the sub-components of a design, and the results are translated to the macroscopic design level, where the ideal application points for the new components are determined. The process is demonstrated below in Figure 3, as per Wennberg *et al.* at KTH Royal Institute of Technology in Stockholm discussed earlier in this report.

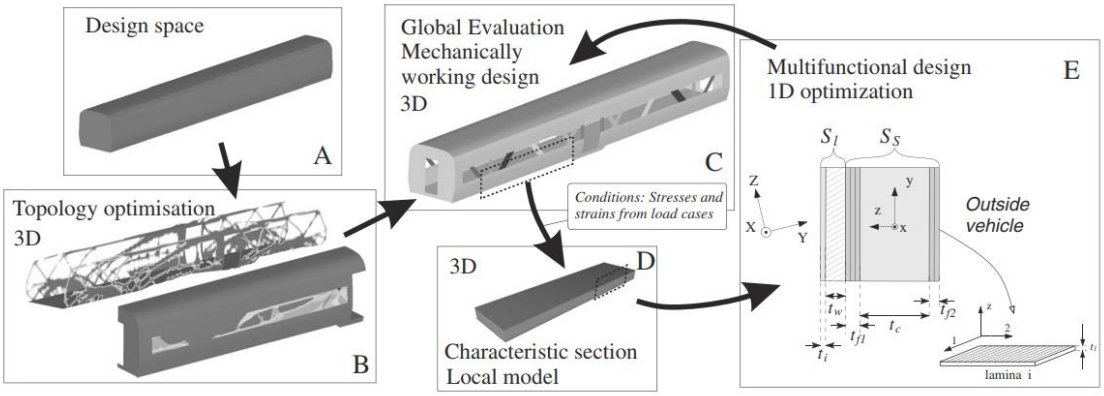

Figure 3.

Overview of MDO [3] [4] [5]. Reprinted from Structural and Multidisciplinary Optimization volume 50, Wennberg & Stichel, Multi-functional design of a composite high-speed train body structure, 475-488, Copyright (2014), with permission from Springer.

A similar example is demonstrated in an article on engineering optimization [171], where an Italian research group redesigned a train roof by emulating the properties of an aluminum honeycomb core sandwich composite at the component level and then carried out a multi-scale design optimization to "map" the locations on the roof where the sandwich composites might be used.

1.4.3 Material Science and Additive Manufacturing

Materials science and the alternative materials emanating from this field of research is a popular topic today in many high-tech industries, particularly in aerospace and transportation. Due to its nature, the alternative materials manufacturing process has affected the production of various highly specific light-weight parts with complicated geometries. Often, the geometry of alternative materials is determined using topology optimization and refined by a shape- or size-optimization assessment [172]. Such techniques enable the creation of periodic structures and lattices and, thus, enable further weight reduction. This section of the literature review will discuss these emerging technologies within the context of rail.

In Germany, Siemens has employed alternative materials to produce parts such as custom arm rests and housing covers for the train's couplers [173]. Though this may seem relatively unimpressive at first glance as it is merely the redesign of an arm rest, Siemens estimates that this process could eventually be used to update older metallic materials with polymers and, thus, drastically reducing the overall weight. At the same time, Bombardier has established a 3D printer in its German plant servicing German-speaking regions in Germany, Austria and Switzerland, with the intent of supplying

parts to prototype trains in the area. General Electric, meanwhile, is planning to expand its alternative materials operations in Cincinnati to service its operations globally [174].

Locally, Bombardier has begun prototype testing with 3D printed parts. The objective over the next five to 10 years is to implement alternative materials in the manufacturing process with functionally graded 3D-printed materials [175]. These are already being tested in several laboratories, one of which has already demonstrated alternative materials within metallic components for industrial use [176].

A major advantage of alternative materials is that they can also extend the service life of older vehicles. The ***Deutsche Bahn*** has recognized this and has identified potential in 3D printing to replace parts on its very old trains for which certain parts are no longer manufactured, and which would be incredibly expensive to produce through traditional manufacturing methods [177]. With this technology, it has become possible to keep certain rail systems running well past their expected service life, reducing maintenance costs and environmental strain from producing new vehicles.

1.4.4 Rail Ties

Traditionally, rail ties have been made of wood, concrete or steel, and have generally proven to be effective for a long period of time. Recently, however, the manufacturing of rail ties comprising of recycled plastics has been developed. Depending on the stiffness required for the rail ties, recycled plastic can provide a viable and eco-friendly alternative to traditional materials, and provide a reasonable compromise between material strength and noise or vibration damping [178].
Each year, 21 million rail ties are decommissioned worldwide. Since many of these rail ties are treated with potentially toxic chemicals, they are not viable for burning and, thus, are increasingly being thrown in landfills. Sticking with traditional materials, the Center for Renewable Carbon has been working alongside the wood-preservative company, Nisus, to produce a safe-for-burning wood preservative [179] [180] [181]. They have created a process that can strip away the preservative after the service life of the ties by emulsifying and treating them. At this point, the wood may be safely burned.

Another new process has been engineered by the University of Minnesota's Natural Resources Research Institute to convert cellulosic biomaterial, such as wood, into a material deemed "torrefied coal," which combusts more efficiently compared to standard wood products or liquid biofuels [182]. This process has now been applied in converting rail ties into clean energy sources by the Coalition for Sustainable Rail [183].

Taking an entirely different approach altogether, a new company in the U.S., Hansen Ties, has recently begun manufacturing rubber railroad ties, which have been approved for use in accordance with American Railway Engineering and Maintenance-of-Way Association (AREMA) standards. They anticipate production of three million rail ties annually each with a life expectancy of 50 years, which is five times that of the standard wooden ties [184] [185]. This new technology, while still in its early stages, may provide a novel solution to reduce excessive burning of wooden rail ties.

Aside from environmental concerns, it is also possible to employ alternative materials to reduce rail-side noise. Getzner GmbH has produced Sylodyn elastic insertion pads, which reduce vibration in rail tracks, thereby reducing wear on the track and train components, as well as lifecycle costs [186].

Noise reduction techniques invented by Brens North America employs a specially created sustainable material using plant materials. This material makes it possible for grass to grow along tracks, which reduces rail-side noise and absorbs pollutions as well as excess heat in the summer, along with the added benefit of making the tracks more visually appealing [187].

Summary

There may be significant opportunities for Canada to increase investments in alternative propulsion, energy efficiency, operational optimization and alternative-material technologies in both passenger and freight rail applications. In this way, Canada could achieve GHG-reduction goals in its transportation sector and improve passenger and freight services, achieving improved operational sustainability in the rail sector overall.

SECTION 2: METHODOLOGY FOR FOCUS GROUP DATA COLLECTION AND ANALYSIS

The main objective of the Transport Canada commissioned CUTRIC rail innovation initiative is to identify the "Top 10" rail innovation technology theme areas that align with Transport Canada's mandate to guide and spur innovation in transportation nationally.

To generate a Top 10 ranking list for Canada, CUTRIC developed a three-part data collection methodology. The first step involves identifying core themes of research and innovation relevant to this dialogue, as judged from a global perspective. These themes are extracted from a preliminary literature review, shared with and approved by Transport Canada. Each theme thus generated creates the basis for a specific consultation session, as shown in Table 4 below.

Table 4.
Location, date and technology themes of all five focus group sessions.

Session	Location	Date	Technology theme
1A	Queen's University, Kingston, ON	November 22, 2018	Alternative propulsion
1B	Metrolinx, Toronto, ON	February 11, 2019	
2	Ballard, Burnaby, BC	April 10, 2019	Energy efficiency
3	University of Waterloo, Waterloo, ON	June 3, 2019	Operational optimization and integrated mobility
4	Bombardier Prototype Centre, St-Bruno, QC	August 8, 2019	Alternative materials

The second step involves developing a semi-structured focus group methodology to create proposed technology theme areas on a group-by-group basis. CUTRIC focus group sessions use a standardized structure to inform and then query participants. Sessions typically commence with informative presentations from industry and academic experts within a given field to initiate the creative thought process among participants, and to ensure participants are aware of state-of-the-art rail technologies globally. Focus group sessions are further structured around industrial categories identifying participants as follows:

- Government stakeholders
- Academic stakeholders
- Private industry stakeholders
- Others, such as transit agencies

Each group has no more than eight participants per group to ensure meaningful internal dialogue within each group given the time constraints of the session. The list of organizations, companies and institutes associated with all participants for each session is attached to this report as Appendix 1.

In Session 1A, was tasked with responding to the general thematic concepts of “opportunities”, “challenges” and “solutions” as they relate to alternative propulsion innovation specifically:

1. Each group is tasked with identifying the top three opportunities related to alternative propulsion innovation in rail across Canada, where “opportunity” is defined as social, environmental, economic and/or technological in nature.
2. Each group is tasked with identifying the top two challenges associated with each of the top two opportunities selected from the group of three originally identified in (1) above.
3. Each group is tasked with proposing solutions for each of the two challenges identified in (2) above.

The template of the focus group questionnaire is attached to this report as Appendix 2.
It is worth mentioning that the outcomes of Session 1A resulted in a broad discussion as to how alternative propulsion could be relevant to the rail sector. While insightful, the session did not produce project-specific results that were focused enough on unique technological innovation opportunities. As a result, with the support of Transport Canada’s staff, CUTRIC implemented a methodological change that affected all subsequent sessions (i.e., Sessions 1B, 2, 3 and 4) to ensure participants would delve further into identifying top technology innovations within each overarching technology theme area, both nationally and globally.

Therefore, Sessions 1B, 2, 3 and 4 focused on project concepts and initiatives as reflected in the template tool used to produce the project theme areas and initiatives, and as documented below in this report. A more structured and detailed focus group template was used for these sessions to enable participants to think through the most relevant aspects of their “top” innovation ideas for rail applications in Canada. The template is attached to this report as Appendix 3.
Overall, to support group dialogue within CUTRIC focus group sessions, several industry- and academic-led presentations are offered to participants as foundational groundwork at the start of the session, upon which technology themes relevant to the Canadian rail innovation landscape can be identified in the short term.

All feedback is documented in real-time and vetted against written notes and session recordings post-factum, resulting in summary outcomes, as discussed in the next section of this report.
The third step in the methodology employed here involves a quantitative and qualitative analysis of the variables emanating from the focus groups described above. CUTRIC researchers apply a structured methodology, both quantitative and qualitative, based on the information obtained through consultation sessions (i.e., Sessions 1B, 2, 3 and 4).

Details of all three parts of the methodology are further discussed in the following sub-sections.

2.1 Focus group Methodology

Focus group research techniques are conventional qualitative data collection methods whereby a small number of participants are engaged in informal but structured group discussion focused around a particular topic or set of ideas. Historically, research involving survey questions catalyzed the development of focus group methodologies, as formalized by the work of two researchers, Paul Lazarsfeld and Robert Merton, in the 1940s [188]. Since then, literature reviews and exploratory interviews among other early-stage data collection methods have been introduced by researchers and used to form the structure and query framework for effective focus group sessions.

A focus group design varies based on the specific agenda of a session and the research question being studied. In general, principles that must be considered when planning focus groups include the standardization of questions, number of focus groups conducted, number of participants per group, and level of moderator involvement. The standardization of questions affects the extent to which focus groups follow a structured protocol and permits open-ended discussions to emerge. In most cases, questions presented by the moderator are structured and targeted to answer a specific research query, as moderators request structured responses. The number of focus groups conducted depends on how participants are divided or segmented, e.g. segmented by employment sector, expertise field or another qualifier [189].

Focus groups typically have between six to 12 participants per group, which is large enough to ensure diversity in the information provided while eliminating the risk of being too large of a group such that the thoughts and opinions of some members may not be heard [188]. CUTRIC imposes group limits of four to six participants, given the need for detailed insight into technology project areas, which large group structures do not allow for.

Lastly, the level of moderator involvement can vary from a low degree, where participants are largely left to discuss topics among themselves and provide opinions, to a high degree, where the moderator asks very pointed questions and strongly guides follow-up discussion [189]. The moderator is generally responsible for facilitating the discussion by prompting participants to speak openly, while balancing the talking time of overly engaged participants to foster contributions from others and to encourage quieter individuals or groups to participate adequately to inform the process. Typically, the moderator has a pre-determined series of questions that structures the focus group dialogue [188]. CUTRIC utilizes a moderate- to high-level of moderator engagement to structure and guide discussions to ensure outcomes align with core methodological goals established by its clients, in this case Transport Canada.

Focus groups can be used for a range of objectives, including gathering preliminary data, aiding in the development of surveys and interview guides, clarifying research findings generated from another method, or establishing the bases for a “next steps” framework for future policy work or future research efforts.

Focus groups can also achieve the following:

- Explore new research areas.
- Explore a topic that is difficult to observe.
- Explore a topic that does not lend itself to observational techniques.
- Explore sensitive topics.
- Collect a concentrated set of observations in a short span.
- Ascertain perspectives and experiences on a topic, especially from those who might otherwise be marginalized [189].

In the present study, CUTRIC has employed a focus group methodology to achieve two goals for Transport Canada:

(1) Explore new research areas;

(2) Establish the bases for a “next steps” framework for future policy work and research efforts.

To record the data derived from a given focus group, it is essential to have two to three researchers (in addition to the moderator) attending to take notes, ideally in real-time. Each researcher's note-taking can be different to capture different types of data inputs (e.g., verbal outputs, non-verbal behaviour, and group dynamics). CUTRIC utilizes a real-time data collection methodology in which researchers collect feedback directly from focus group plenary portions of the session during which a rapporteur reports on the group's discussion outcomes. By recording these outcomes and simultaneously projecting the outcomes in a spreadsheet divided by query (so that all participants can view their outputs on a display screen), CUTRIC enables participants to see feedback being recorded in real-time so they may clarify whether CUTRIC researchers have properly or incorrectly understood participant feedback before the end of the session.

The focus group methodology has been useful in the present study as it provides large amounts of data on a topic in a short period of time, while also enabling access to topics that might otherwise be unobservable. The focus group methodology used here also provides assurance that data collected directly targets the researcher and client's topic of interest. Lastly, it allows participants to compare their experiences and opinions against one another, potentially providing for a group consensus or group division of opinions on a given topic [189]. This creates a setting wherein participants can listen to one another's responses, provide rebuttals, reach a consensus, or at least devise an agreed-to summary of opinions about reasonable inputs, which can bring a value to the sessions that is not achievable in one-on-one interviews [188].

2.2 Summary of Focus Group Session Technology Theme Areas

This section of the report summarizes the rail innovation technology theme areas that emanated from CUTRIC's focus group sessions carried out over an 18-month period across Canada. Further details associated with each area are available in Appendix 4. In total, participants identified 18 technology theme areas, while five were removed by Transport Canada in a first round of qualitative assessment, as they did not reflect specific technologies that Transport Canada has the means to advance by virtue of its innovation mandate. The remaining 13 technology theme areas were further explored using quantitative and qualitative analyses to provide an ultimate ranking, as described in following sections. Table 5 demonstrates the main attributes associated with these 13 technology theme areas.

Table 5.
Main attributes of technology theme areas identified by focus group participants.

Session theme	Technology theme area	Sector	Cost	TRL	Time to execute (years)	Number of stakeholders
Session 1B: Alternative Propulsion	Catenary-Free Electrification Rail Facilities	Industry	$10M– $20M	7–9	< 3	3
	Hydrail Switching Yards	Industry	Phase 1: $250K Phase 2: $50M Phase 3: TBD	7–8	3–4	6
	Hydrail Passenger	Industry/ community	Phase 1: $45M Phase 2: $55M Phase 3: $250M Total: $350M	Integration piece: 6 Phase 1: 9	Phase 1: 1 Phase 2: 1.5 Phase 3: 2	5
	Hydrail Long Distance Freight	Government/ academics	$20M– $100M	Start: 3–4 Prototype: 5–6	5	9
Session 2: Energy Efficiency	Artificial Intelligence Fleet Management	Operators/ manufacturers	$5M– $10M	7– 8	< 5	3
	Propulsion Technology Simulation Tool	manufacturers / integrators	$3M	4–6	1.5	6
	CNG/Hydrogen-to-Diesel Complementation	Academics	Natural Gas: $10M Hydrogen: $10M Total: $20M	4–9	5	3
	Rail Electrification	Government	$10M	5–7	5	5
Session 3: Operational Optimization	Toronto Union Station Flow and Capacity	Academics	< $1M	3–6	2–3	5
Session 4: Alternative Materials	Rail Car Demonstrator	Industry	$50M–$100M	3–7	Design: 3 Fabrication:1.5 Validation: 1.5 Total: 6	5
	3D Printing for Rail Parts	Industry	$5M–$10M	7–9	5	4
	Hybrid Light-Weight Structure	Academics	$10M	3–6	5	4
	Sandwiched Sheet Polymers Testing and Development	Academics	$5M–$10M	3–6	5	5

2.2.1 Session 1B: Alternative Propulsion

In Session 1B, the first technology theme area identified by industry-sector participants is "Catenary Free Electrification Rail Facilities." The main goal of this project is to integrate energy storage to support peak usage and demand management of energy loads overall, as well as generate economic savings for catenary-free electrification systems. Participants identified a cost for this project as ranging from C$10 million to C$20 million, starting at a technology readiness level (TRL) of seven (i.e. an integration trial) and ending at TRL nine. The total time to execute the project is expected to be less than three years.

The second technology theme area identified by industry-sector participants in this session is "Hydrail Switching Yards." The intention of this project is to integrate high-powered locomotives for freight rail in switching yards, which participants view as more feasible compared to electrifying an entire rail line.

This project aims to advance the hydrogen economy in Canada and is seen as beneficial from environmental, economic, and innovation standpoints. The project is a phased initiative, starting with hydrogen-powered locomotives in a switching yard and extending to potential main freight lines that could start at C$250,000 for a feasibility study, growing into a C$50 million project involving switching-yard applications. A third phase proposed by participants includes a long-term application to larger main freight lines with predicted costs ranging widely depending upon the size and scope of the deployment. The entire process is expected to take three to four years with a TRL advancement from level seven to level eight, given that participants do not view the transference of technology from switching yards into a very small main freight line as achieving full commercialization of the technology.

The third technology theme area identified by industry-sector participants is "Hydrail Passenger Rail." The main focus of this technology is on hydrail and hydrogen fuel applications for passenger and light-rail systems, specifically passenger mobility aimed at advancing the hydrogen ecosystem in Canada. Participants identified a phased initiative, with phase one being a one-year effort involving six months to launch and an additional six months to build six kilometres of rail line, costing approximately C$45 million. The total cost of this project is estimated to be C$350 million with an ultimate TRL ending at level nine. The project targets the objective of fundamentally altering the hydrogen mobility landscape in Canada.

The fourth technology theme area is "Hydrail Long Distance Freight," as identified by government- and academic-sector participants. Participants identify the main objective of this project as assessing the economic break-even point for using hydrogen tenders that would carry hydrogen to support long-haul hydrail freight lines. The estimated cost of this project is C$20 million to C$100 million with a five-year timeline starting at a TRL of three to four to develop, design and conduct a feasibility analysis of a tender. The project ends at TRL five to six with prototyping.

2.2.2 Session 2: Energy Efficiency

In Session 2, the first technology theme area identified by participants is "Artificial Intelligence Fleet Management," proposed by operators and manufacturers from industry sectors. The objective is to use data collection, information management, and AI tools to optimize operational efficiency for existing large rail fleets. The cost of this project is estimated to be C$5 million to C$10 million. Participants believe it would take less than five years to complete (including a data collection phase) and that it would advance the technology from TRL seven to eight.

The second technology theme area is "Propulsion Technology Simulation Tool", also identified by manufacturers and technology integrators. Participants identify the objective of this theme area to be the development of a simulation tool for propulsion systems that can precisely model and simulate the operation of a "hyper"-locomotive, and which could determine the most suitable alternative fuels or energy storage devices needed to ensure maximum operational optimization through energy efficiency. Participants estimate it would take 18 months to develop such a simulation tool costing C$3 million, starting at a TRL of four and ending at six.

The third technology theme area participants identify is "CNG/Hydrogen-to-Diesel Complementation", as proposed by academic-sector participants. The focus of this technology is on developing data-driven tools to optimize other propulsion technologies that could complement diesel propulsion systems. Hence, predictive feasibility modelling is critical in this project with a focus on natural gas and hydrogen fuels with an estimated cost of C$10 million for each round of modelling. The timeline

for this project is projected to be five years, which would move the technology forward from a current TRL of four to nine.

The fourth technology theme area government-sector participants identify is “Rail Electrification”. Participants identify this theme area as focusing on the development of energy management systems to support rail electrification. The objective of the project would be to integrate energy management systems, energy storage systems and the grid at an advanced level to support the rail sector specifically. Participants identify the fact there is room for improvement in Canada in terms of energy management and energy systems integration for rail and transit applications. Participants also identify several additional benefits for the electricity grid system overall from such initiatives, including grid resiliency, energy systems resiliency, climate change resiliency, and GHG-emissions reductions, which would arise from investment in this technology theme area. Participants estimate a cost of C$10 million with a five-year timeline to move the technology from TRL five to seven to enable full optimization outcomes.

2.2.3 Session 3: Operational Optimization and Integrated Mobility

In Session 3, participants identify “Toronto Union Station Flow and Capacity” as a core theme of interest and potential, wherein the objective of the project is to optimize Toronto Union Station and its corridors from both train and passenger flow perspectives. Investment in this technology theme area would enable the development of a simulation tool assessing those predictive flows. Although Toronto Union Station is an example of a station that needs improvement, other stations across Canada are also identified by participants throughout the session. The cost of this project is estimated to be less than C$1 million with a completion timeline of two to three years and advancing a simulation tool from a TRL of three to six. Participants note this project could fundamentally improve the lives commuter rail riders throughout the GTA.

2.2.4 Session 4: Alternative Materials

In Session 4, the first technology theme area identified by industry-sector participants is the “Rail Car Demonstrator” initiative. The objective is the assessment of different materials used in a demonstrator car. The group focus is on testing materials for safety standards. Participants identify the objective as designing, manufacturing, validating, operating, and engaging new materials in a demonstrator car. Participants identify this theme area as a six-year initiative, costing C$50 million to C$100 million given the combined costs of materials and building the demonstrator car. Such an investment would progress alternative materials for rail applications from a TRL of three to seven.

The second technology theme area participants identify is “3D Printing for Rail Parts.” Industry-sector participants propose this project based on the implementation of design principles and standards for 3D printing. Participants highlight the belief that 3D printing creates an opportunity for rail operators to print parts for rail cars that are very old, where the manufacturer may no longer produce the parts in question, or which may be extremely expensive to manufacture for maintenance and operations purposes. In these cases, refurbishment-focused 3D printing could provide parts much more cheaply compared to traditionally manufactured parts, even though there are challenges to consider with regards to the safety, security and standardization of such parts. Participants estimate the project would take five years to complete, and cost C$5 million to C$10 million, advancing 3D printing for rail applications from a current TRL of seven to nine.

The third technology theme area identified by academic-sector participants is “Hybrid Light-Weight Structure”, focusing on the need for the demonstration of a hybrid light-weight structure that uses new

materials (similar to the "Rail Demonstrator Car" theme noted above by a previous group). This group dialogue focuses on hybrid light-weight material structures specifically. The main goal of this project is to develop hybrid light-weight structures that can be tested through to certification with the certification process itself being developed as part of the initiative. Participants estimate the project would take five years to complete costing C$10 million and advancing the TRL of the technology from three to six.

The final technology theme area academic-sector participants identify is "Sandwiched Sheet Polymers Testing and Development". This project identifies an initiative that uses aluminum in sandwich polymers to develop new materials for safety and light-weight operational savings. This is a five-year project costing C$5 million to C$10 million with a TRL movement from level three to six.

2.3 Quantitative Analysis

Based on the four core themes explored in focus group format above, several quantitative and qualitative variables emerged as useful empirical categories to help identify a list of "Top 10" rail innovation areas potentially relevant to the Canadian rail sector.

A score from one to 10 is assigned to each scoring category based on the quantification rubric defined in Table 6. A higher score for each variable indicates stronger merits for focusing on the given technology in the context of the Canadian rail sector. Scores are equally weighted across all four variables in this study. Based on the scoring method identified here, researchers tabulate total scores across all four variables to generate final quantities to numerically rank technology theme areas against one another from the highest ranking (1st) to the lowest ranking (10th).

Table 6 demonstrates the four quantitative variables along with their ranges and scores given to each variable range.

Table 6.
Four quantitative variables, ranges and scores.

Cost		**TRL**				**Timeline**		**Stakeholders**	
Million $ (CAD)	Score	Final TRL	Score	TRL jump	Score	Number of years	Score	Number of stakeholders	Score
<5	2	6	1	1	2	>4.5	1	>7	2
5 to 15	4	7	4	2	4	3.5 to 4.5	4	6	4
15 to 25	6	8	7	3	6	2.5 to 3.5	7	5	6
25 to 75	8	9	10	4	8	<2.5	10	4	8
>75	10	n/a	n/a	5	10	n/a	n/a	<3	10

The section below offers a brief description of the four quantitative variables and how quantitative scores are defined for each variable.

1) Cost and proposed investment

Technology theme areas with the largest financial investments obtain the highest score in this variable. For instance, a technology theme area with C$100 million investment acquires a higher score than one with a total proposed cost of C$1 million, because projects with a higher level of proposed investment are assumed to create more jobs and help advance the economy further (capital intensity being assumed to correlate with job creation in this instance).

Figure 4 shows the discrete distribution of cost variables across all 13 technology theme areas.

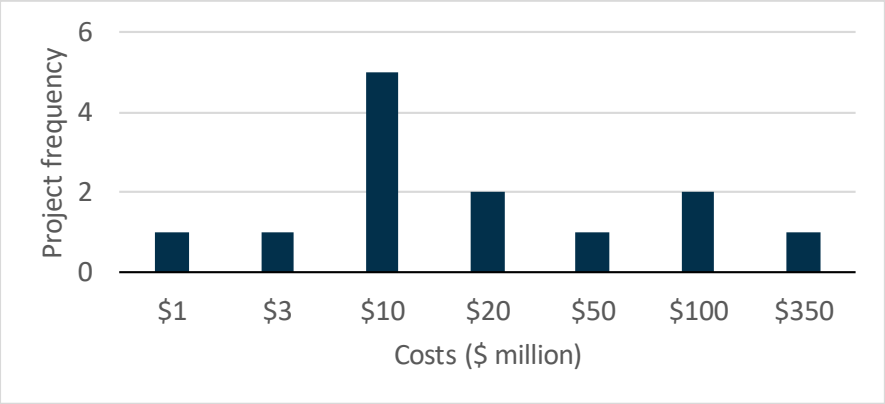

Figure 4. Distribution of cost variable across all rail innovation projects identified in focus group sessions.

2) Timeline to completion

The timeline variable assumes projects with a shorter completion timeline are more valuable overall to rail innovation in Canada given the speed of completion is assumed to be correlated to innovation impact. Therefore, projects with the shortest completion timeline obtain the highest score.

Figure 5 shows the distribution of total years to completion across all technology theme areas.

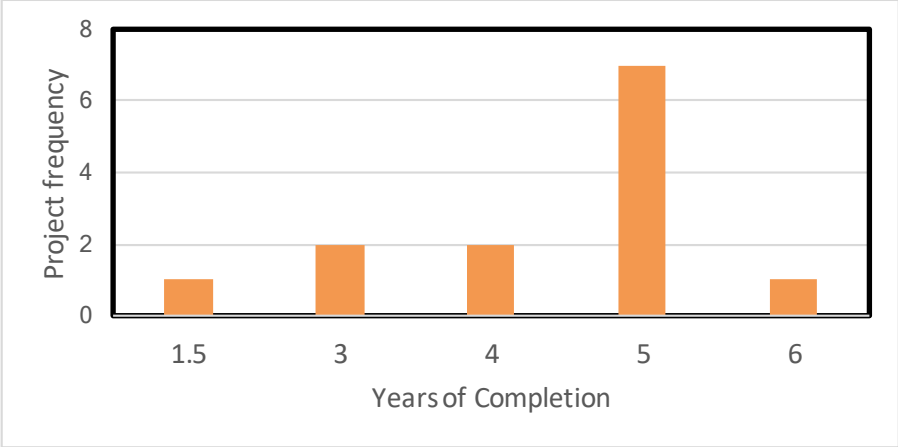

Figure 5. Distribution of timeline variable across all rail-innovation projects identified in focus group sessions.

3) Number of core stakeholders

In this variable, the lowest number of core stakeholders involved in each proposed project obtains the highest score, as it is assumed the technology theme area is generally less complex when fewer collaborators are involved. In this variable, each core "stakeholder" refers to a category of a stakeholder, such as "manufacturer", "operator", "utility" or "government", rather than specific organizations, such as Bombardier or VIA Rail.

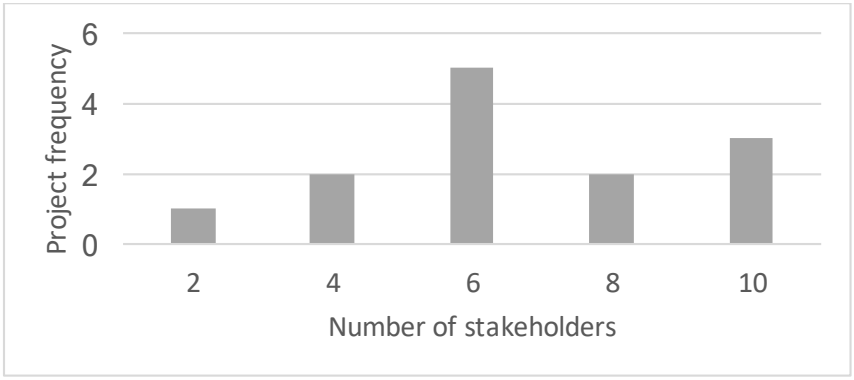

Figure 6. Distribution of stakeholder variable across all rail innovation projects identified in focus group sessions.

4) Technology readiness level (TRL)

In this variable, TRL is used to estimate the maturity of technologies over the course of the proposed project timeline. In general, "TRL" is a measure used to estimate the maturity of a technology from a marketplace perspective [190]. A TRL of "one" means the technology is at the earliest stage of scientific conceptualization and only conceptual in nature. A TRL of "nine" means the technology is fully commercialized and ready for market-place sales. CUTRIC considers final TRL in the quantitative ranking assigning the highest scores in this variable to technology theme areas that achieve the highest TRL at the end of the proposed project. This is because Transport Canada places greater emphasis on developing projects that can be commercialized.

Figure 7 shows the distribution of final TRL across all 13 technology theme areas.

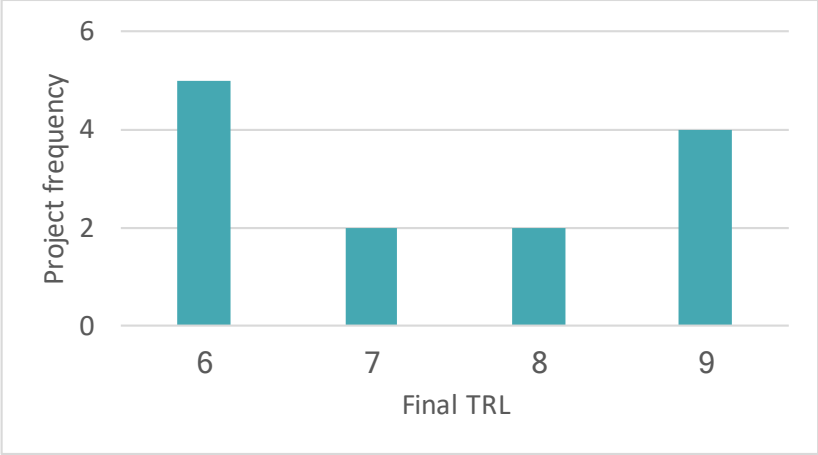

Figure 7. Distribution of final-TRL variable across all rail innovation projects identified in focus group sessions

Figure 8. Quantitative rank scoring of rail-innovation "Top 10" projects.

2.3.2 Sensitivity Analysis

Table 8 recreates ranking results with a sensitivity analysis integrated, which removes the cost variable to observe the total impact caused by the project cost variable on overall rankings. This re-evaluation demonstrates that a project's proposed cost (i.e. as proposed by participants) does not significantly influence its ranking overall.

Similar to rankings shown in Table 7, most alternative propulsion projects are still ranked at the top, while most alternative materials projects are ranked at the bottom.

Importantly, the overall "Top 10" technology theme areas remain the same in both rankings.

Table 8.

Quantitative ranking of rail projects when removing cost variable. The scores for each variable are shown in red.

Nominated project	Session	Sector	Final TRL/ score	Number of years/ score	Number of stakeholders/ score	Total score	Project rank
Catenary-Free Electrification Rail Facilities	1B	Industry	9	3	3	27	High "Top 10"
			10	7	10		
CNG/Hydrogen-to-Diesel Complementation	2	Academic	9	5	3	21	
			10	1	10		
Hydrail Passenger	1B	Industry	9	4	5	20	
			10	4	6		
3D Printing for Rail Parts	4	Industry	9	5	4	19	Medium "Top 10"
			10	1	8		
AI Fleet Management	2	Operators/ manufacturers	8	5	3	18	
			7	1	10		
Hydrail Switching Yards	1B	Industry/Community	8	4	6	15+	
			7	4	4		
Propulsion Technology Simulation Tool	2	manufacturers /technology integrators	6	1.5	6	15	
			1	10	4		
Toronto Union Station Flow and Capacity	3	Academic	6	3	5	14	
			1	7	6		
Rail Electrification	2	Government/public sector	7	5	5	11+	Low "Top 10"
			4	1	6		
Rail Car Demonstrator	4	Industry	7	6	5	11	
			4	1	6		
Hybrid Light-weight Structure	4	Academic	6	5	4	10	Outside the "Top 10"
			1	1	8		
Sandwiched Sheet Polymers Testing and Development	4	Academic	6	5	5	8	
			1	1	6		
Hydrail Long Distance Freight	1B	Government/Academic	6	5	9	4	
			1	1	2		

2.4 Qualitative Analysis: Data Analysis through Content Analysis

Qualitative content analysis is a research method used to subjectively interpret the content of text data through a systematic classification process of coding and identifying themes or patterns. In broad terms, the objective of qualitative content analysis is to organize large quantities of text into much fewer content categories. The categories represent patterns or themes that are directly shown in the text or which can be derived through additional analysis. The categories are then assessed in relation to one another to uncover the implications and teachings of the completed study [191].

As previously mentioned, CUTRIC focus groups are created with stakeholders' interests in mind, and each group is categorized as private industry, academia, transit agency or government representative. Stakeholders are sub-divided into groups of four to six participants, categorized by sector and guided by CUTRIC's moderator. Groups are directed to discuss specific questions and offer targeted summary points, which are then shared in plenary mode. The moderator guides this discussion and asks clarifying or follow-up questions wherever appropriate. Feedback taken by accompanying CUTRIC research staff are compiled in real-time for participant viewing.

As part of this process, participants in this rail innovation scan were asked to identify top economic, environmental, social and technological opportunities associated with each proposed technology theme area for rail applications in Canada. Participants were also asked to identify critical challenges and potential solutions associated with those opportunities, as identified for each technology theme area.

Below is the description of qualitative categories that emerge from consultation session qualitative data outputs.

1) **Economic**

This variable relates to the thematic content analysis of proposed economic opportunities and challenges cited per project. Economic concepts such as job creation, advancing the Canadian economy, commercialization that supports export potential constitute defining aspects of the "economic" variable.

2) **Environmental**

This variable relates to opportunities cited per project that mainly promote concepts of GHG reductions, carbon elimination or other pollutant reductions, and noise reduction. Interestingly, no challenges emerge associated with this qualitative variable based on consultation session output data.

3) **Social**

This variable relates to opportunities and challenges relevant to the concepts of health and mobility.

4) **Operational**

This variable relates to opportunities and challenges that consider levels of fleet operation and fleet complexity associated with each project and theme area.

5) Technological

This variable relates to proposed technological opportunities and challenges such as innovation, technology readiness, and the advancement of industry needs versus risks posed through technological investments.

2.4.1 Summary of Qualitative Data Analysis

CUTRIC engages in the thematic coding of qualitative data outputs collected from focus group sessions to make sense of qualitative data by separating plenary and categorized commentary offered by participants into organized themes. Data from the focus group sessions are coded into economic, environmental, social, operational and technological categories to identify specific opportunities and challenges associated with each technology theme area, as proposed by participants. Once all data are coded according to the pre-defined variables, the software runs a frequency analysis for each category to sort all feedback provided by participants into the main concepts of "opportunities," "challenges" and "solutions". (Qualitative data software, NVivo 12 Plus, is used to conduct this portion of analysis).

Figures 9 and 10 show how all 13 projects compare based on qualitative inputs provided by participants associated with each technology theme area. Note the percentage "coverage", or frequency, identified here constitutes a summation of *all* qualitative data across all categories identified for each technology theme area. The qualitative analysis provides a deeper analysis of each technology theme area, and can be used to build upon quantitative rankings offered previously. The quantitative rank for each technology theme area is shown in the figures below to provide a link between the cited coverage, or frequency, of opportunities and challenges and the proposed quantitative project ranking. The technology theme areas are colour-coded according to their session category (i.e. alternative propulsion: purple, energy efficiency: green, operational optimization: yellow, and alternative materials: orange).

Figure 9 demonstrates that – similar to the results from the quantitative ranking – alternative propulsion projects demonstrate higher frequencies of positive "opportunities" emanating from the various qualitative variables pre-defined in this study, while most of the alternative materials projects demonstrate lower frequencies of overall positive opportunities, as identified by consultation session participants. At the same time, alternative propulsion projects are also associated with a higher coverage, or frequency, of challenges cited. This is logical given that participants are asked to identify at least one challenge associated with each opportunity identified; thus, the number of challenges increases with the number of opportunities identified for each project.

Within opportunities, the most frequent themes participants identify across all projects are "economic" followed by "environmental".

While insightful, there are limitations associated with qualitative methodologies based on focus group feedback. These analyses rely heavily on the number and types of participants assigned to each group. For example, some groups might have been more vocal than others, and therefore they may have articulated more opportunities for their defined projects comparatively, independently of whether more objective opportunities actually exist in the industrial, academic or transit world. Because of this limitation, qualitative measures are not used directly to establish the "Top 10" final project ranking. Rather, and as previously mentioned, these measures are used to help distinguish projects that are tied quantitatively, and which are marked with a "+" on their quantitative rankings, in Table 7 and Table 8.

Qualitative measures also help Transport Canada obtain additional socio-economic and environmental insights into every technology theme area proposed by participants in this study. Note that Figure 9 represents the percentage of opportunities, or "coverage" of dialogue, associated with positive keyword references coded within discussions associated with opportunities for each specific project in which the total discussion of each project adds up to 100 percent. Appendix 4 contains the main points of discussion for each technology theme area, including opportunities, challenges and solutions.

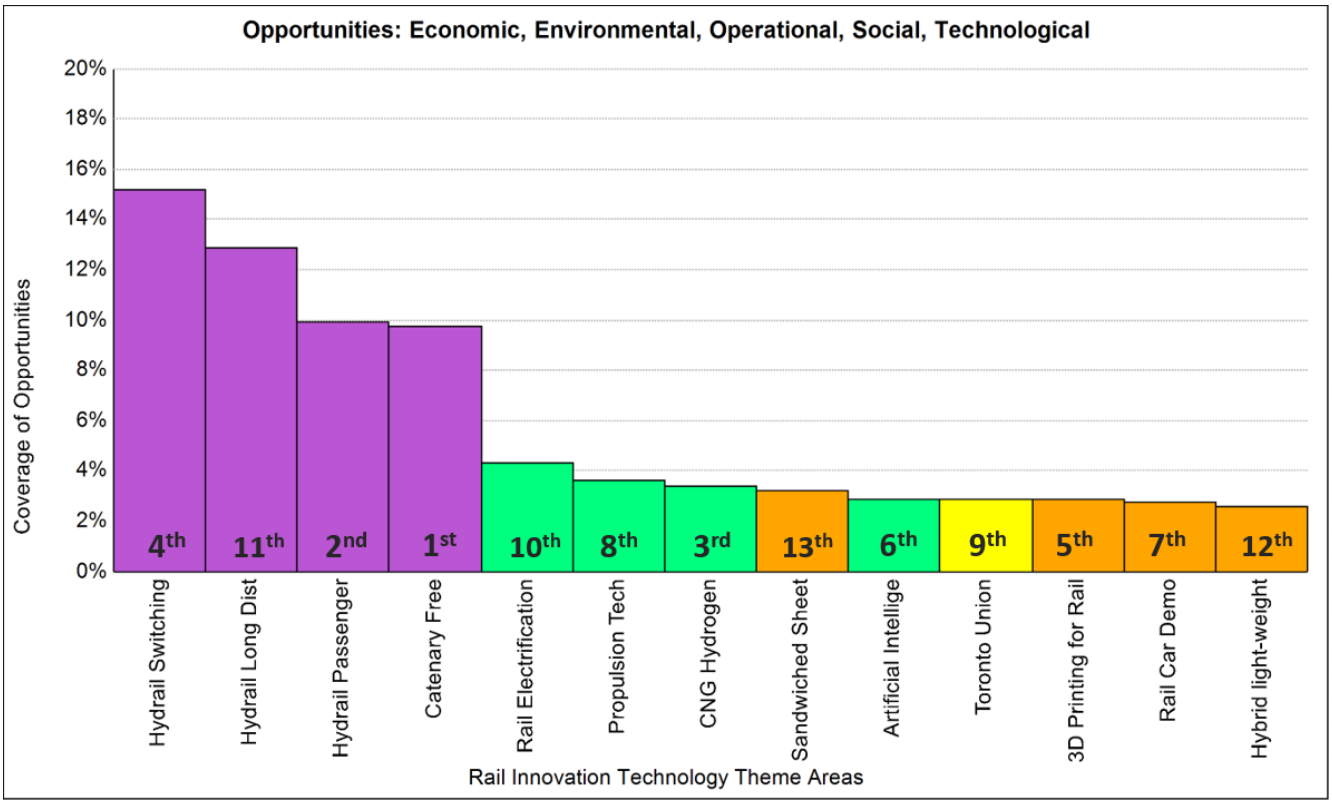

Figure 9. Comparing the coverage of qualitatively-cited "opportunity" themes identified by participants across all rail innovation technology theme areas. (Quantitative rankings are shown inside the bar.)

Legend: Purple: Alternative Propulsion
Green: Energy Efficiency
Yellow: Operational Optimization
Orange: Alternative Materials

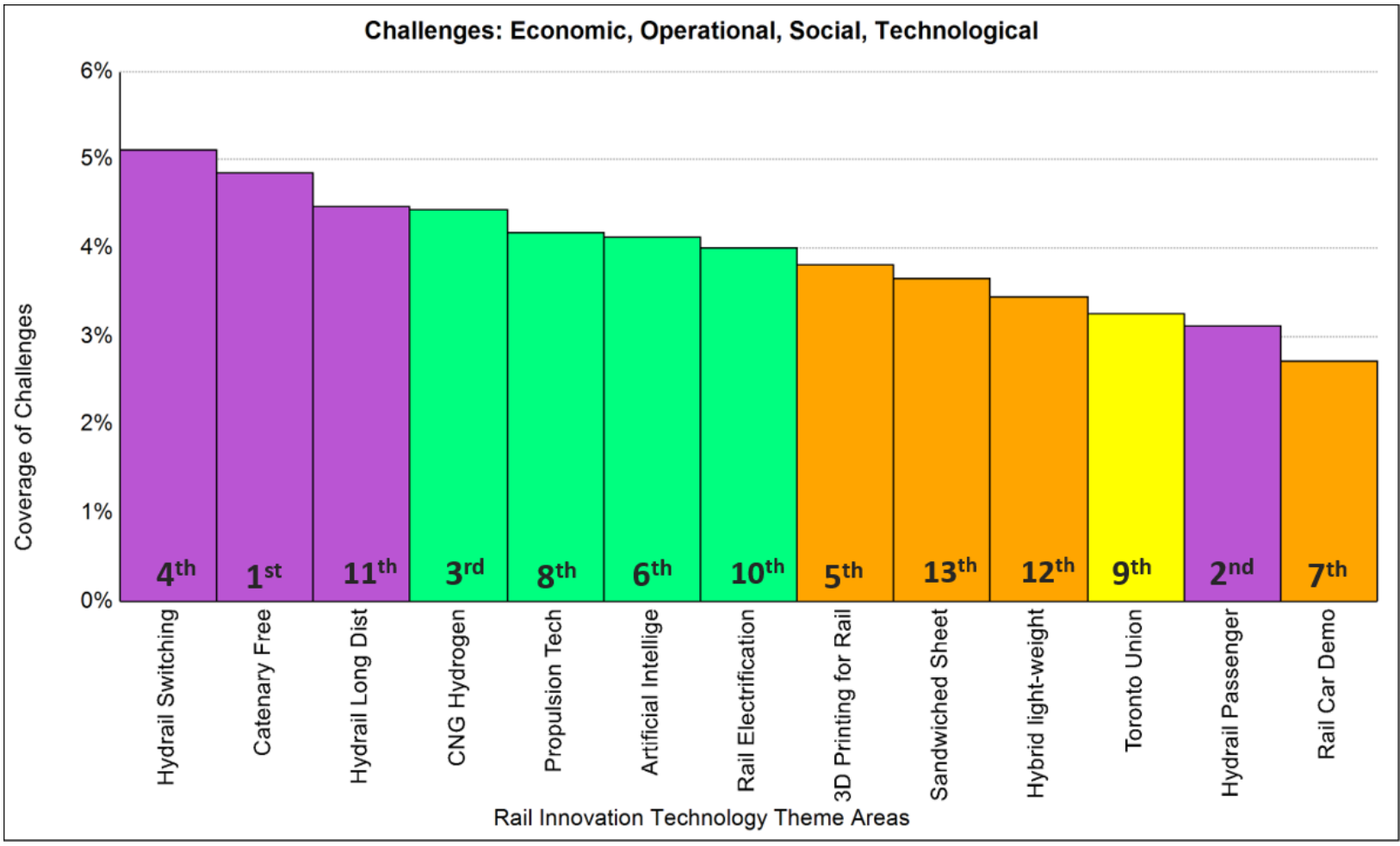

Figure 10. Comparing coverage of qualitative "challenge" themes identified by participants across all rail innovation technology theme areas. The quantitative ranks are shown inside the bar.

Legend: Purple: Alternative Propulsion
Green: Energy Efficiency
Yellow: Operational Optimization
Orange: Alternative Materials

2.5 Quantitative and Qualitative Analysis of "Top 3" Ranked Technology Theme Areas

This section reviews the qualitative opportunities and challenges associated with the "Top 3" technology theme areas ranked in this study.

1st Ranked: Catenary-Free Electrification Rail Facilities

Participants in this group identify the potential implementation of a stationary and mobile energy storage integration effort that supports off-peak usage for grid management and the electrification of catenary-free rail systems. Based on qualitative content analysis for this group, the concept of "energy" and the "need to focus on electricity and storage capacity" emerge as prominent qualitative discussion themes.

The main opportunities participants identify focus on the economics of building a business case for non-transportation and transportation applications, achieving GHG-emissions reductions, finding applications for energy storage in transportation, and saving customers money across the entire rail network. Participants also identify several challenges, such as the uncertainty of electricity pricing over the long-term, the immaturity of the supply chain across the ecosystem, and perceived safety issues for large-scale ESS. This highlights the fact there are substantive challenges associated with this theme area that need to be addressed through public policy or industry commercialization efforts before launching a specific technology project of this nature in Canada.

Figures 11a and 11b show the categorized opportunities and challenges associated with the "Catenary-Free Electrification Rail Facilities" project theme.

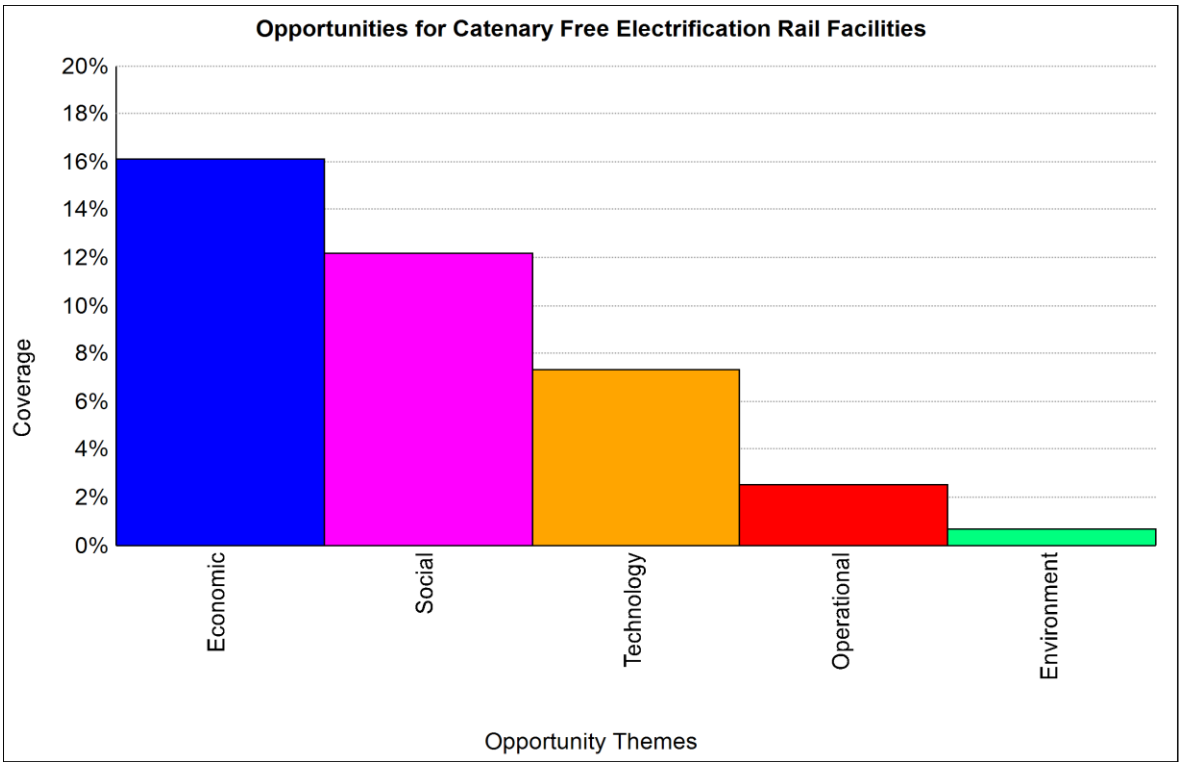

Figure 11a. Categorized opportunities associated with Catenary Free Electrification Rail Facilities.

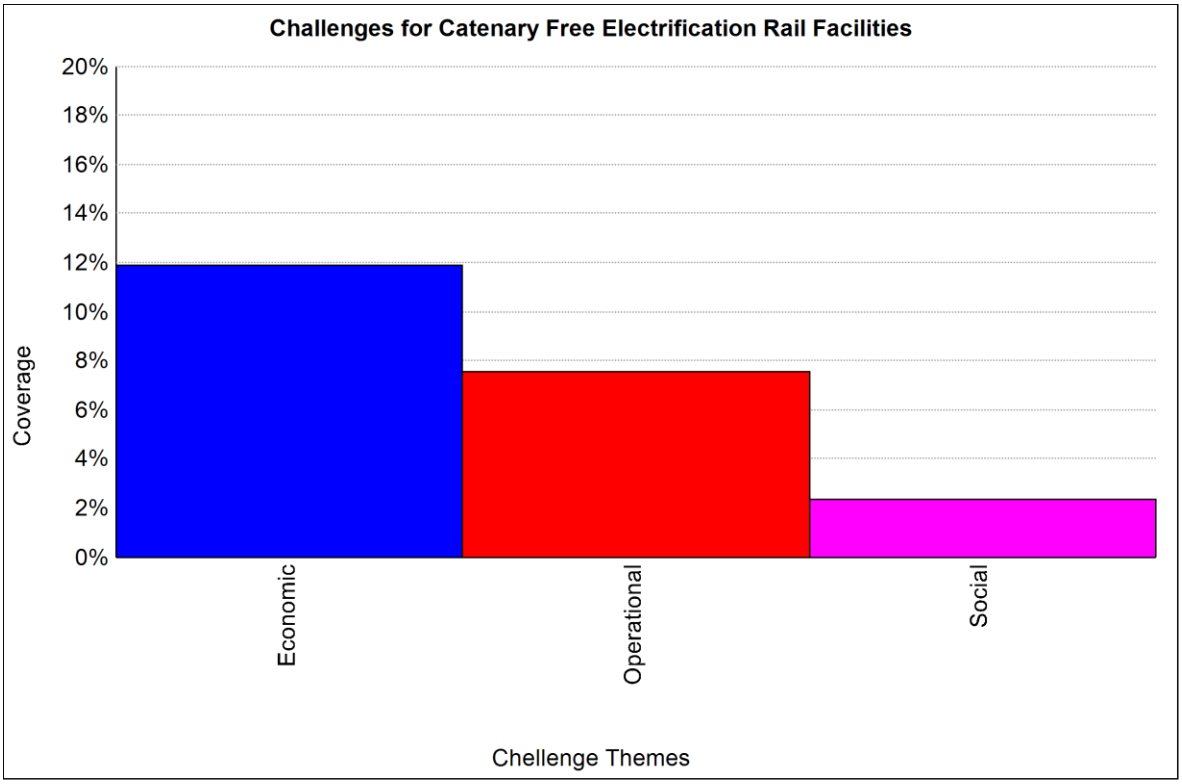

Figure 11b. Categorized challenges associated with Catenary Free Electrification Rail Facilities.

2nd Ranked: Hydrail Passenger

Participants in this group identify the fact hydrail and hydrogen fuel for passenger and light-rail applications will certainly grow the hydrogen energy system across Canada if implemented. Qualitative content analysis identifies "social," "economic" and "community" as key qualitative themes that emanate from this focus group.

Accordingly, the main ideas this group highlight relate to social impact, community-building, and socio-economic/equality opportunities within the rail sector, ranging from an operator to user perspective of the system. The opportunities identified address the development of local economic growth (e.g., a Canadian-made retrofit kit), the need to reduce emissions regionally, and the need to create a collaborative national innovative hub for hydrail technologies. Participants also identify the initiative as nurturing political opportunities in sustainable technology.

Participants identify qualitative challenges as well, including the lack of engagement of indigenous communities in establishing core design principles around rail systems in Canada. Additional challenges identified include limited funding sources, as well as social "NIMBYism" ("not-in-my-backyard") issues in communities that integrate hydrogen mobility to transport people.

Figures 12a and 12b show the categorized opportunities and challenges associated with the "Hydrail Passenger" project theme.

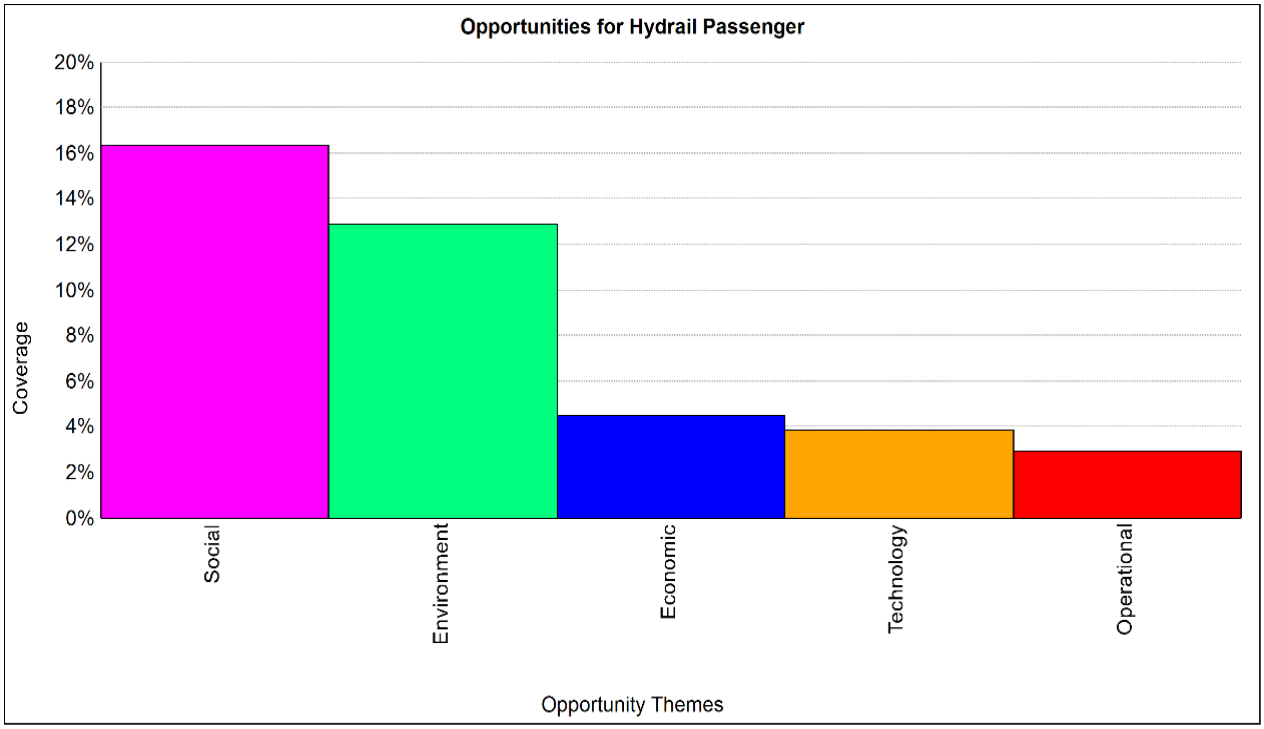

Figure 12a. Categorized opportunities associated with Hydrail Passenger.

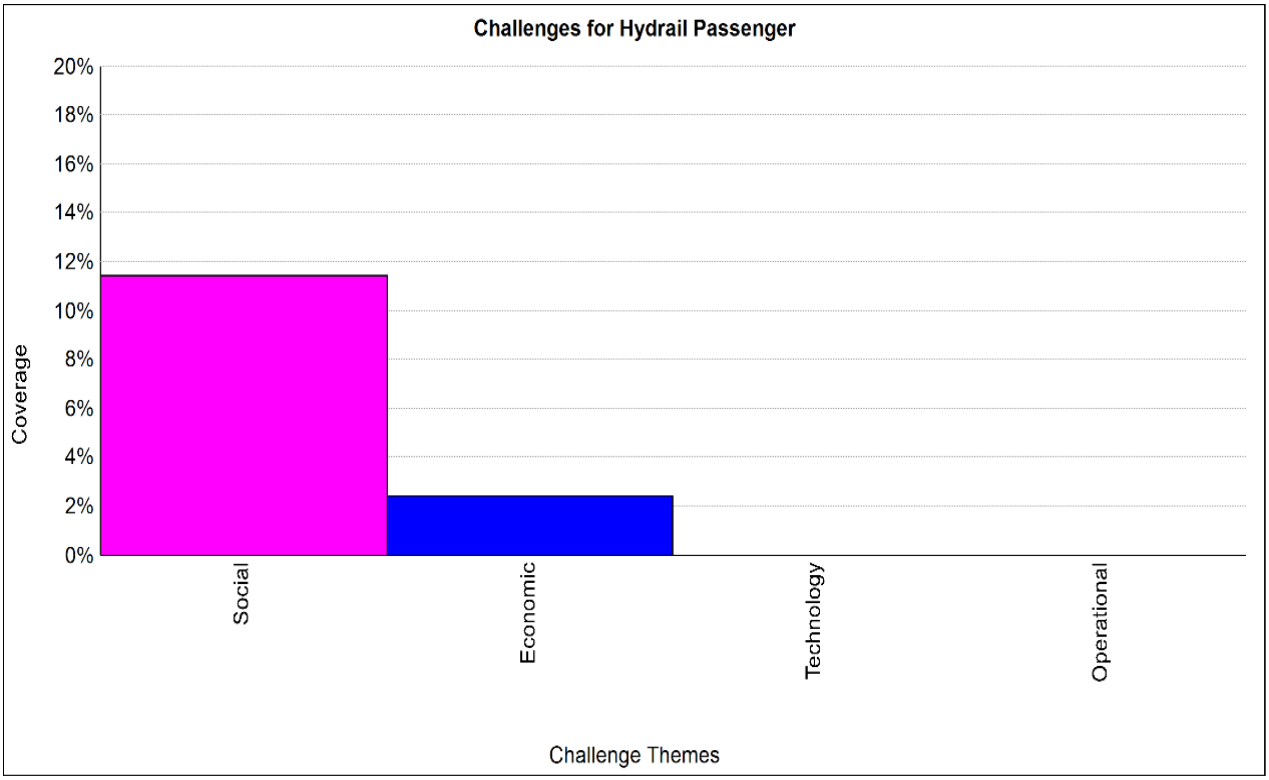

Figure 12b. Categorized challenges associated with Hydrail Passenger.

3rd Ranked: Compressed Natural Gas (CNG)/Hydrogen (H2)-to-Diesel Complementation

Participants in this group identify opportunities and challenges associated with the development of data-based tools that optimize the incorporation of other propulsion technologies complementing diesel systems, specifically CNG and hydrogen fuels. The participants discuss the integration of these fuels across portions of a rail fleet from operations, economic and overall systems perspectives. Based on qualitative content analysis, the main focus of this group's discussion is the "operational" achievement and "technical" developments that would emanate from such an initiative. Important opportunities identified for this project include the development of a global market for Canadian manufacturers, protecting the environment, and operational cost reductions via effective systems solutions.

Figures 13a and 13b show the categorized opportunities and challenges associated with the "Compressed Natural Gas (CNG)/Hydrogen (H2)-to-Diesel Complementation" project theme.

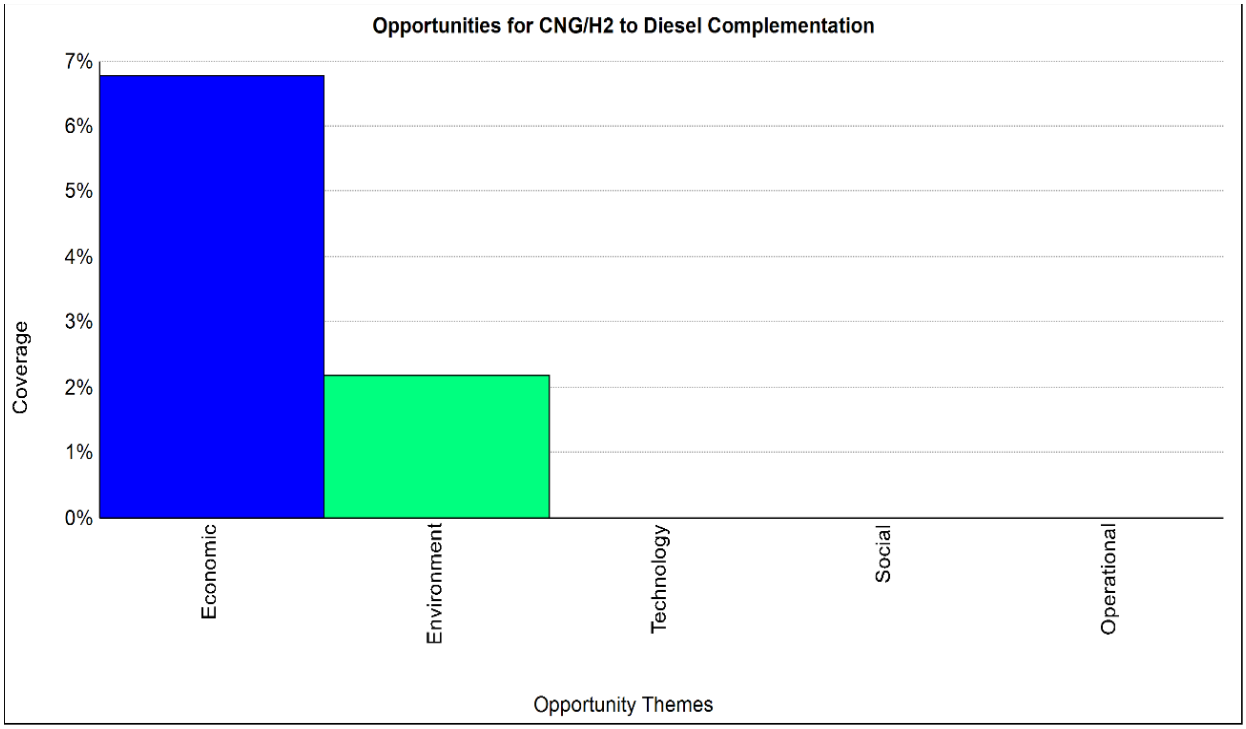

Figure 13a. Categorized opportunities associated with CNG/Hydrogen to Diesel Complementation.

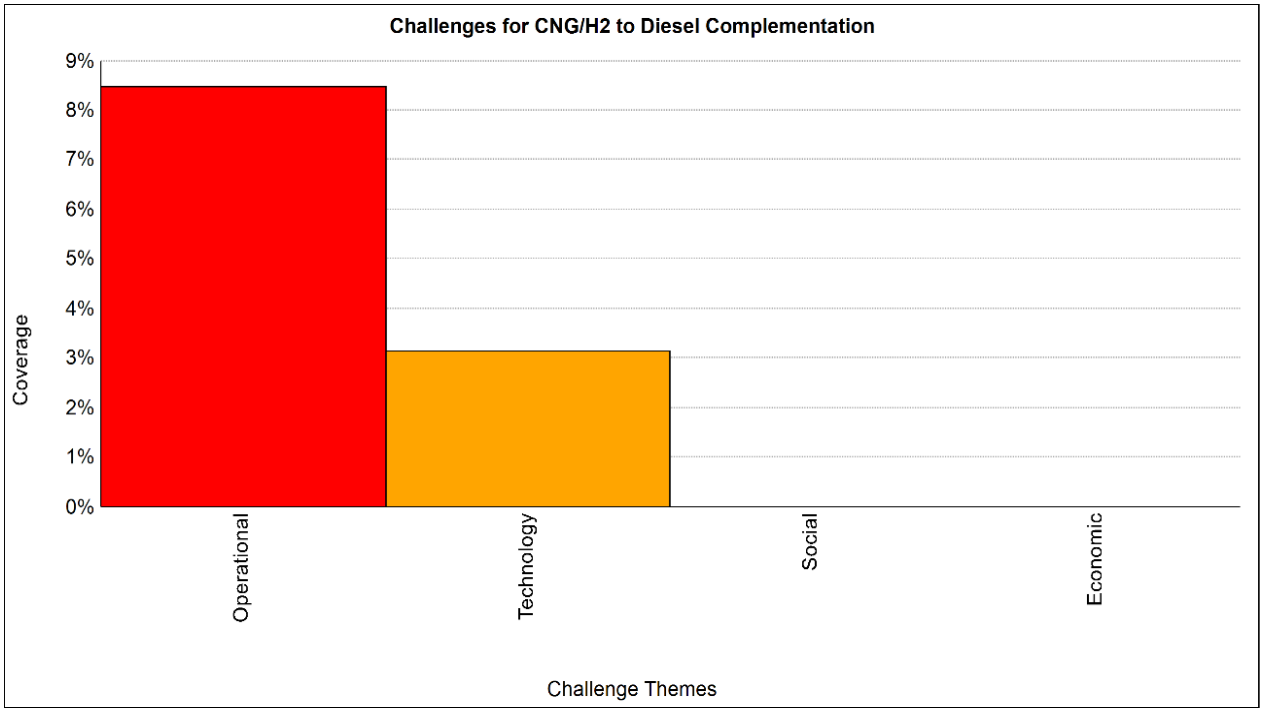

Figure 13b. Categorized challenges associated with CNG/Hydrogen to Diesel Complementation.

SECTION 3: CONCLUSIONS AND DISCUSSIONS

3.1 Main Outcomes of Consultation Sessions

3.1.1 Session 1A: Alternative Propulsion

CUTRIC's Rail Innovation Focus Group Session 1A hosted at Queen's University on November 22, 2018 with participants from government (federal and provincial), academia and industry sectoral groups, offers some initial general opportunities to consider, as identified by participants engaged in structured discussion apropos of developing and deploying innovative alternative propulsion technologies in Canada. These include the following qualitative outcomes:

- In the short term, there is an opportunity in Canada to electrify switch engines using advanced alternative propulsion systems in train yards to reduce noise and GHG emissions.
- A world-class "Rail Innovation Incubator Hub" could be set up in Canada to finance, test, develop and commercialize rail-innovation intellectual property valuable to the global rail industry.
- Canadian rail industries have a strong desire to support domestic advanced rail-technologies, such as hydrail and wireless power transfer technologies. Currently, many advanced rail technologies developed in Canada are exported globally but not used domestically; therefore, Canadians have contributed to, but have not benefited from, these technologies.
- There is an opportunity for Canada to leapfrog catenary electrification systems in rail and enter directly into advanced non-catenary systems to showcase innovative and socially attractive technologies to the public.
- There are immediate opportunities for VIA Rail, Metrolinx's RER and RTM's "Exo" rail systems to integrate advanced alternative propulsion systems in their imminent procurements.

3.1.2 Session 1B: Alternative Propulsion

In Rail Innovation Focus Group Session 1B, hosted at Metrolinx offices in Toronto on February 11, 2019, additional transit agencies are integrated into the discussion. Compared to session 1A, Session 1B focuses more intently on identifying and characterizing specific advancements in alternative propulsion technologies *in situ*.

Importantly, although this session addresses all low-carbon alternative propulsion options, participants identify hydrogen as the most important technology within the rail sector in Canada. Additionally, all of the technology options recommended in this session include some form of electrification.

Specifically, Session 1B participants articulate the need to develop and demonstrate hydrogen fuel cell based electric rail ("hydrail") technologies within Canada as one of the most beneficial ways to grow the economy, while addressing rail-technology needs that are aligned with environmental emissions reduction goals. This could include the use of hydrogen fuel as part of auxiliary power systems onboard rail vehicles as a natural starting point, or initial complement to fossil fuel propulsion systems, which would allow industry stakeholders to become familiar with alternative propulsion

technologies at a small scale level before large-scale fleet deployments emerge that focus more on main propulsion systems.

In this session, manufacturers of rail products, cities and transit agency participants all raise qualitative points focusing on the potential positive applications of hydrogen fuel cell electric technologies for both passenger and freight rail across Canada. Heavy-duty rail operators in the session identify several challenges associated with the upfront infrastructure costs for such technology deployments.

In general, participants iterate the fact Canada is still considered a global leader in fuel cell electric vehicle (FCEV) technology innovation and could, therefore, also lead in hydrail technologies. However, participants also state that global reputation is waning as a lack of domestic hydrogen propulsion systems commercialization initiatives and demonstrations projects undermine the reputation of Canada as a global hydrogen *leader*. While many countries are earnestly developing FCEV technologies and building hydrail systems to compete with Canada, Canadians are not continuously investing in, developing or demonstrating these systems locally. If this continues, participants contend, Canada's leadership position in FCEV technologies, and its potential leadership in hydrail applications, will falter and be consumed by global competitors that can build on commercial clientele outside of this country. This may trigger globalized domestic companies to move their headquarters to jurisdictions where there is a "pull" in the marketplace in terms of clientele adopting hydrogen propulsion technologies.

To realize hydrail implementation, participants note Canadian transit and rail operators need to address several technology adoption challenges. These include the fear among transit and transportation systems that investing in environmental technologies still possess an unacceptable uncertainty (or perceived uncertainty), which is combined with an ongoing lack of "systems planning" from an energy-transportation transformation standpoint. In the case of the latter challenge, participants note that while utilities, petroleum producers and natural gas industry players across Canada are all interested in hydrogen-fuel generation and distribution opportunities, they have little to no strategic alignment with transportation operators in the country.

Additional high-level conclusions emanating from session 1B include the following considerations regarding alternative propulsion rail innovation technology themes relevant and critical to Canada's economic and transportation growth:

- Rail operators and utilities will need to partner to develop an effective set of strategies for particular applications (i.e., the Ottawa-Montreal corridor) to ensure that safe and technologically optimized "systems" electrification efforts are built into any demonstration project or integration project.
- Innovation in the rail sector in alternative propulsion in Canada will help to develop "transference" technologies (e.g., motor, power electronic, onboard storage, fuel cell generators and hydrogen fueling) and distribution mechanisms relevant to other propulsion industries such as buses, coaches, trucks, cars and aerospace.
    - Innovations in other sectors – including automotive, aerospace, and even digital technologies – could help to further spur rail innovation in areas of cross- pollinating potential (e.g., electrification, autonomy, connectivity, light-weighting, etc.).
- Innovation in the rail sector in alternative propulsion in Canada will require an education campaign co-led and co-developed by the rail sector and the government to ensure

communities are made aware of the benefits and are informed adequately about the risks (or inaccuracy of perceived risks) associated with hydrogen fueling or other alternative propulsion technologies crossing their communities in rail applications.

- Regular communications within and across rail sector stakeholders, including manufacturers, operators, utilities and academics, is required to continually identify low-hanging fruit for demonstration and integration projects in Canada, due to the newness of the technologies and the infancy of the alternative-fuels industry (including hydrogen production for mobility applications) in the country. Consultation sessions such as the CUTRIC-led Transport Canada focus group initiative can serve only as a starting point for communications of this sort. An ongoing national rail innovation working group for the industry could be established to push forward specific project ideas, generate industry engagement, and move toward funded project-scoping activities in the interests of the industry as well as the local communities that would benefit from innovation by the industry.
- Important to keep in mind, however, is that an overarching focus on alternative propulsion innovation in the rail sector may overshadow the significant emission reductions achieved through the growth of the rail sector in general. As noted by industry participants, the transference of freight loads from truck to rail reduces emissions overall, regardless of powertrain technology. Shifting from higher emissions trucking to highly efficient rail on its own could address many of the freight-related GHG-emission concerns Canadians have, although this solution does not address the job growth motivating factors behind technology development efforts – namely, new technology-based job creation in Canada, or advanced energy (and grid) systems development allied to alternative propulsion in rail.

3.1.3 Session 2: Energy Efficiency

Session 2 is dedicated to a review of energy-efficient technologies for the railway industry. As explained by rail operators, CN and CP, energy efficiency has improved, and fuel consumption has been reduced in Canadian freight rail over the past several decades. However, participants indicate there is still much potential for further energy efficiency improvements in both freight and passenger rail applications.

Participants offer several insights into solutions currently available for improving Canadian rail energy efficiencies, such as deploying pilot projects for hydrail, embedding energy storage systems to ensure the harvesting of braking energy, and using AI to analyze big data collected from rail systems to reduce wasted propulsion emissions based on non-optimal idling, track usage, or routing of railcars.

Further engagement is required to fully assess all opportunities related to energy efficiency in rail applications, including the need to analyze and compare different options for improving energy efficiency system-wide, and the need to reduce the risk of trialling and investment toward new and disruptive technologies.

Participants note further that rail operators lack the expertise needed to adequately or effectively apply AI to analyze their current data sets. Universities can perform these tasks but often cannot access sufficient real-time proprietary industry data to offer outputs of immediate relevance to the industry. As such, collaborations between universities and rail operators need to be fostered in the domain of data driven real-time (AI-enabled) energy efficiency analysis. Universities can provide the know-how, and operators can provide the data. Such collaborations can train future highly qualified personnel (HQP) who would graduate with needed futuristic knowledge of AI as applied to the rail industry, as well as improved energy efficiency for the rail industry overall.

Additional high-level conclusions emanating from Session 2 include the following high-level considerations relevant and critical to Canada's economic and transportation growth:

- Comparative studies that assess how other jurisdictions are implementing energy-efficient rail innovation can assist the Canadian rail industry in building better business cases regarding these technologies.
- The Government of Canada can develop more effective policies and regulations that support the advancement of Canadian railways by forcing the internalization of the costs of energy inefficiencies (e.g., through rigorous carbon pricing), which positively alter the business case for investment into energy efficient solutions in the near-term future.
- Both short- and long-term research, development and demonstration projects are important to advance the Canadian rail industry.
- Passenger and freight rail systems are currently separate in technology planning and strategic investments, as well as actual operations. There may be opportunities to cross-pollinate between the two areas e.g., opportunity to move freight and passenger rail cars in the same train.
- Urban rail presents unrealized potential for improving energy efficiency by using ESSs and optimizing urban operations. Generating data sets is key to understanding how to improve efficiencies and where to invest battery storage systems for optimal deployment. As trusted relationships are critical for sharing and analyzing collected data, one possible solution is to aggregate and anonymize rail data so that it can be made widely available. This would create the business case to share data sets and analyses with a wider world of research-based innovators, as opposed to only enabling a few paid consultants to access those data on contract-by-contract bases.
- Utilities are necessary partners in these initiatives and should have a seat at the table to provide input into transportation-electrification initiatives, including ESS, because the technical specifications and roles utilities will play within the energy capture and storage systems associated with electrified rail in the future are still not clear and need to be built out across Canada.
- Possible pilot-project applications for hydrail demonstrating energy efficiency through alternative propulsion systems should explore the following routes:
    a. Victoria to Parksville: there is potential to upgrade the existing unused 177-kilometre track for tourism
    b. Chilliwack to Surrey: there is potential to create a 97-kilometre commuter train.
- Alternatively, a yard switcher can be retrofitted for pilot projects to pull passenger cars along while demonstrating the technologies in question.
- As the scale of hydrogen applications grow, the price of hydrogen will decrease. Modelling can help to predict where the volume-based break points are for hydrogen-diesel pricing parity for the industry.

3.1.4 Session 3: Operational Optimization and Integrated Mobility

Session 3 focuses on technologies that optimize rail operations beyond energy efficiency alone. Session 3 contains valuable outcomes from group discussions, showing there is potential for optimizing railway operations across Canada, especially in Southern Ontario.

Participants from rail operators, academic institutions, governments and consulting companies suggest developing a centralized railway-operation and optimization control system for different operators (private and public). A centralized control system can control passenger and freight trains simultaneously to increase railway network efficiency, which is preferable to each rail operator managing its own operation control system. Under a decentralized control system, it takes longer to coordinate with other parties' needs, ultimately leading to low efficiencies across the network.

Participants also suggest that building extra tracks or sidings for passenger rail systems, such as VIA Rail and the GO Train in the Greater Toronto and Hamilton Areas, would immediately improve network efficiency, as several rail corridors have already reached capacity and will continue to exceed those limits in the near future leading to train delays and scheduling constraints. Extra tracks will improve railway energy efficiency and reduce costly congestion and delays.

Integrated mobility – with optimized bus, shuttle and train scheduling for passengers – would increase ridership across the network leading to the optimization of revenue kilometres travelled, as well as increase the fare-base of the network system wide. This requires data integration projects between local transit agencies, regional rail and inter-city rail systems – something that both RTM and GO Transit have not been able to achieve effectively over the years.

Although participants in this session did not focus heavily on the application of big data and AI to railway maintenance as part of an operations solution set, global literature suggests this is a prominent theme of potential relevance to the Canadian landscape. Applying AI and big data technologies are especially important in improving and maintaining the safety levels required of railways in the near future, which indirectly improves railway network operational efficiencies by reducing the number of accidents and breakdowns.

Additional high-level conclusions emanating from Session 3 include the following high-level considerations relevant and critical to Canada's economic and transportation growth:

- Optimization efforts must necessarily obtain input from Ontario's Ministry of Transportation, the City of Toronto, CN and CP in terms of operational optimization for the Greater Toronto and Hamilton Areas.
- Projects and investments must pursue a holistic and integrated vision for passenger mobility and freight rail rather than following the current approach, which separates and fragments both networks and systems logistically and technologically, leading to non-optimized use of rail infrastructure across Canada.
- Optimization of the rail system depends on an integrated mobility strategy for buses and trains with an integrated ticketing system.
- Planning and protecting railway corridors to ensure their (re)usability in the future is critical; neglecting them renders them unusable for repurposing in the future leading to long-term inefficiencies.

3.1.5 Session 4: Alternative Materials

Session 4 focuses on the technology of alternative materials, including discussions about the potential for light-weighting and optimization of vehicle assets and lifecycles through materials innovation in railways across Canada.

Participants recommend extending membership of the European-wide Shift2Rail network of nations and corporations beyond Europe can help to standardize materials innovations globally and reduce global price-points for high-end advanced materials components and designs. There is potential to create a Canada-EU materials data sharing mechanism through a public data trust building on the CUTRIC-Shift2Rail memorandum of understanding (MOU) that already exists, and which should be leveraged more robustly in the near-term future, and building on the Canada-European Union free trade agreement already in place.

High-level conclusions emanating from Session 4 include the following considerations regarding alternative materials in rail innovation relevant and critical to Canada's economic and transportation growth:

- Developing new materials for systems-wide rail applications by leveraging the federally-funded materials innovation "supercluster" initiative based in Ontario could kick-start a nation-wide material innovation initiative in this sector.
- Similarly, developing AI features that support materials innovation and design in the rail sector by leveraging the federally-funded Scale.AI "supercluster" initiative based in Quebec, could kick-start a nation-wide material innovation initiative in this sector.
- Developing lighter high-strength elevated structures and infrastructure for use with lighter vehicles could create more space in urban environments and enable more corridors for future rail applications by building corridors above ground.
- Exploring experiences in the automotive sector in the future might serve as useful comparative models for nation-wide innovation initiatives in this space, as the automotive sector in the U.S. has developed supplier-led pilot project demonstrations with ultra-light steel body materials, which were intended to change customer preferences, and which helped suppliers to change course and align with similar materials standards. Although, any comparison with the automotive sector could be stymied by the larger procurement volumes at play in the case of automobiles.

3.2 Analysis of Hydrail Considerations within a Global Context

A review of global innovation policies and technology-development goals regarding hydrogen transportation systems shows that as a form of rail innovation technology, hydrail (including propulsion and fueling systems) falls within the context of a global hydrogen ecosystem that integrates hydrogen fuel cells, electrolysers, compression and storage systems, and multiple allied integration technologies. Hydrail technologies are specifically reviewed in this section because alternative propulsion projects for rail applications, and specifically hydrogen applications, rank among the highest in the "Top 10" lists documented in earlier sections of this report, both in quantitative and qualitative considerations.

Hydrogen fuel cell vehicles, particularly hydrogen propelled buses, are in operation in various parts of the world as an affordable and operable zero-tailpipe emissions public transit solution. In addition to employing a clean-energy resource to help decarbonize the economy, several benefits, including the lower level of long-term infrastructure investment needed, compared with other electrified propulsion options (e.g., power-line installation, charging infrastructure installation and storage capacity installation for battery electric mobility), to suit operational requirements and routes/schedules has been cited as an important attribute of hydrogen fuel cell powered transportation systems [192].

The EU and its member states have taken direct policy action in addressing transportation-related GHG emissions through hydrogen electrification. The objective of these policy efforts is to reduce climate change inducing GHG emissions while improving local air quality across Europe by displacing diesel and gasoline powertrains. As part of Paris Climate commitments, the EU set a collective target of reducing GHGs by 80 per cent compared with 1990 levels by 2050. Decarbonizing the public transportation system is expected to reduce emissions by 95 per cent from the transportation sector overall. In addition, many European cities have planned to phase out diesel buses completely to enable a 100 per cent zero-emissions bus fleet within the next few years [193]. Through multiple programs, such as Clean Hydrogen in European Cities (CHIC) and the Joint Initiative for Hydrogen Vehicles across Europe (JIVE), more than 900 fuel cell electric buses have been purchased or are planned to be deployed in Europe [194] [195].

In China, by comparison, rapid economic development over the past 20 years of liberalization efforts within the country has taken a toll on the state's national air quality. Rising income levels and urban density has caused higher rates of transportation consumption and vehicle ownership. Vehicular emissions in China have contributed 33 per cent of all air pollution (i.e., carbon dioxide equivalent pollutants) in major Chinese cities. The need for low- and zero-emission transportation systems has taken precedence at the political and technological levels of discourse. As a result, the Chinese State Council supported developing FCEBs through rebates of up to 500,000 Chinese Yuan (CNY), equivalent to C$95,000 [196]. Ballard Power Systems partnered with Guangdong Nation-Synergy and Broad Ocean Motors to demonstrate a large-scale FCEB fleet in which nearly 1,000 FCEBs were deployed in China by the end of 2017 [197] [198]. These FCEBs were integrated the FCvelocity HD85 fuel cell module with a battery capacity of 36 kWh and 25 kilograms of hydrogen storage onboard with a carrying capacity of 80 passengers [195].

Japan has long been a champion of hydrogen propulsion technologies. The country has been involved in hydrogen fuel cell demonstrations for more than two decades and boasts to have one of the most advanced hydrogen energy and hydrogen fuel cell technology development programs in the world. Declaring a commitment to reduce GHGs by 25 per cent from 1990 levels by 2020, Japan has invested in an innovative energy policy calling for the creation of a "hydrogen society" in the near future. As part of this effort, the Japanese government has been supporting research and development of hydrogen fuel cell technology across the country for more than a decade. Prior to the COVID-19 pandemic and subsequent cancellation of the 2020 Olympics, Japan had planned to have more than 100 FCEBs deployed during the 2020 Olympics [195].

The U.S. emits some of the world's highest levels of GHGs with the transportation industry accounting for about 30 per cent of its domestic energy consumption and resultant emissions. In light of the need to reduce GHG emissions, hydrogen fuel cells have been proposed as a novel technology that may help to transcend the hurdles presented by range, power and emissions for all mobility modes including rail. With a lower recurring maintenance cost expected to lower lifetime costs overall, fuel cells are considered more efficient than petroleum-based power generators and can be economically and technically viable long term [199] [61]. According to the latest information published by the

National Renewable Energy Laboratory (NREL), there are a total of 32 FCEBs that actively serve in the U.S. and projects involving a total of 35 buses are already being planned [195].

Although Canada does not have any operational FCEBs, nor is it currently proposing a hydrail line in earnest (outside of early-stage feasibility analyses at Metrolinx), the City of Mississauga has supported bids to procure 10 FCEBs for deployment in Mississauga by 2020 using a locally installed ecosystem of hydrogen production, compression, distribution and storage in the city itself.

These progressive movements in developing a hydrogen ecosystem and hydrogen-propelled transportation system relate to the hydrail dialogue because many of the same manufacturers (e.g., Ballard Power Systems and Hydrogenics (now Cummins) on fuel cell technology, Siemens and ABB on hydrogen energy storage and integration, and Enbridge on hydrogen production, etc.) are active across all transportation modes from bus to coach, as well as rail.

3.3 Technology Theme Area Analysis Summary

As previously discussed, most alternative propulsion projects are ranked top of the list, while most alternative materials projects are ranked nearer to the bottom of the list. Clustering and frequency analysis demonstrate optimal technology theme areas range between C$10 to C$20 million in total cost with an average of five years to complete, and involve approximately six stakeholder categories (outside of government funding). Results of the focus group sessions documented above also show that projects demonstrating a final TRL of six are mostly those that were proposed by the academic sector, while projects demonstrating a final TRL of nine are mostly industry-proposed.

This clustering shows that proposed technology theme areas are not simple projects to deploy or launch given the average completion timeline and the number of stakeholders necessarily involved, including manufacturers, utilities, fleet operators, and cities. Additionally, competing commercial priorities that emerge in plenary focus group discussions across all sessions, along with the realities of Canadian constitutional divisions of responsibilities and regulatory responsibilities that affect rail innovation initiatives that shape passenger and freight train travel as it traverses the nation, render rail innovation more complex than local transit systems innovation.

Importantly, alternative propulsion technologies, especially “hydrail”, need to be supported by a wider range of stakeholders across Canada if the nation is to maintain or grow its international position as a leader in the global hydrogen innovation economy. It is worth mentioning that several jurisdictions worldwide, such as South Australia and India, are currently actively considering large-scale hydrogen technology integration for the transportation sector, while Canada is not yet doing so.

Lastly, although rail innovation technology areas could be publicly related as a matter of national pride, there is currently no federal strategic plan for passenger rail mobility in Canada with set targets. The lack of a passenger rail strategic plan creates ambiguity for the sector, and renders it difficult for industrial partners to determine where to invest or extend their rail initiatives.

The technology themes ranked in this report could help to develop an initial rail innovation strategy for Canada integrating industry, academia and government officials in a constructive collaboration to help prioritize innovative deployment goals to position Canada as global leader across the areas of alternative propulsion, energy efficiency, systems optimization and materials sciences for rail applications.

3.4 Considerations

Given the highly structured nature of CUTRIC focus group sessions, participants are offered the opportunity to share roundtable feedback post-consultation to explore additional considerations, concepts and innovation ideas allied to alternative propulsion in rail applications in Canada.
Other considerations are also added to this list as a result of quantitative and qualitative data analysis.

Government

- It is important to be aware of competing priorities, divergent stakeholder views and priorities, constitutional divisions of responsibilities and regulatory considerations, which have important implications for rail innovation projects in Canada.
- The Government of Canada, in general, can advance regulatory actions that are performance-oriented and support economic, safety and environmental objectives, as well as support Canadian competitiveness.
- Any proposed projects in alternative propulsion would need to be accepted and supported by a wide array of stakeholders in Canada.

Academia

- Canada's legacy in petroleum extraction and usage should be recognized as representative of a sector that needs to be integrated into any future strategy to achieve "buy in" or, at a minimum, to avoid opposition, as the country transitions to alternative fuels for propulsion and other applications in the future.
- Rail innovation projects can be publicly related as a matter of national pride – i.e., Canadian nation-building investments that create jobs, improve mobility and address climate change reduction goals in tandem.

Industry

- Several TRL seven and TRL eight project deployment opportunities for alternative propulsion in Canada may include the following integration zones:
    - Rail yards, in general.
    - The Ottawa-Kingston-Toronto line, or Montreal-Toronto line, for hydrail testing.
    - The Toronto Union-Pearson line, "UP Express".
    - Specific long-distance freight lines given their route pathways through hydrogen production zones.
        - This would require a feasibility analysis of appropriate routes to target in partnership with CN, CP and utilities that would play a role in hydrogen production (through electrolysis) or producers of steam methane reformed hydrogen from natural gas sources in Canada.
- Canada must accelerate the adoption of hydrail projects to maintain the footprint of Ballard Power Systems and Hydrogenics (now Cummins) in the country, among other hydrogen innovation players.
- Some entity, whether government-led or an industry-led association or consortium, needs to take ongoing responsibility for educating fleets to ensure up-to-date information dissemination to them and their city or regional funders, as well as fleet decision-makers and operations teams due to the fast-changing nature of technology in this sector.

- Integrating transit agencies and power providers and utilities in the same discussion as part of this consultation is critical going forward. Although utilities in Canada may be presently disconnected from discussion about hydrogen production and distribution, they are essential partners in building a hydrogen ecosystem.
- Industry plays a constructive role in the development and evolution of standards to exploit fully the promise of technical innovation. As such, the integration of industrial associations in this process can build certainty in the development of new technology advances.

3.5 Concluding Remarks

A literature scan of global innovation in the rail sector has demonstrated that Canada is beginning to lag behind several developed and developing nations in the design, integration, launch and trialing of alternative propulsion applications in the rail sector. It also suggests that Canada is behind in the commercialization of those technologies, including electrified HSR, battery electric (catenary-supported and non-catenary) systems applications and hydrogen electric propulsion applications despite possessing advanced technological development and expertise in this area.

A literature review of the global landscape associated with the hydrogen propulsion and generation industries, specifically, demonstrates that many countries recognize multiple benefits associated with the technology with most FCEV trials and projects focused currently on bus applications. The transition of these technologies to rail applications is highly feasible given the cross-pollination of several major companies in the shuttle, bus, coach, truck and rail sectors regarding “electrification” of propulsion systems. These major companies include, but are not limited to, Ballard Power Systems, Hydrogenics (now Cummins), ABB, Siemens, Alstom, Bombardier (recently) and electric utilities that are now emerging as the fuel generators, providers and distributors of the future.

Given the challenging business case associated with significant capital investments into the infrastructure required for freight trial applications of hydrail, it is likely that near-term hydrail applications will arise most feasibly along high-ridership routes among Canada’s major passenger rail lines, such as the Ottawa-Montreal or Windsor-Toronto corridors. These corridors constitute the most accessible, cost-efficient, and experimentally valuable project and testing areas for Transport Canada to consider in the near term. The ridership revenues they generate could constitute reasonable financial offsets for high-cost technology trialing in the future.

This study carried out by CUTRIC offers a preliminary analysis aimed at generating an overview of the current Canadian landscape in terms of innovation in rail technologies. Further detailed studies and deep-dive focus group and interview sessions with experts in each technology themed area identified in this report are required to fully capture the picture of potential rail innovation in Canada, and to determine whether high-level proposals for industry investment in the areas identified would, in fact, come to fruition given the right governmental or public policy levers.

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APPENDIX 1: LIST OF ORGANIZATIONS AND INSTITUTES OF FOCUS GROUP SESSIONS

Sessions	Organizations/ institutes of Participants
1A	- ABB - Bombardier - Carleton University - Environment and Climate Change Canada - Hydrogenics Corp - Infranovate - Kingston Economic Development Corporation - National Research Council Canada - Natural Resources Canada - Parsons - Queen's University - Railway Association of Canada - Siemens - Tech-K.O., Inc. - TELLIGENCE Group - Thales Canada - Transport Canada - University of Windsor - University of Ontario Institute of Technology - UOIT
1B	- AECOM - Alstom - ANI Networking - Ballard Power System - Bombardier - Cariboo Central Railroad Contracting Ltd - CN - Danielson Consulting - Environment and Climate Change Canada - Gannett Fleming - Hydrogen Business Council - Hydrogenics - IBI Group - IGC - Infrastructure Ontario - InnovÉÉ - Jacobs - Metrolinx - Niso Energy Corporation - Parsons - Pragmatic Solutions

	- QP - Queen's University - Rosemary Frei - Ryerson University - Siemens - SNC Lavalin - TfNSW - Tech-K.O., Inc. - Telehop / Alast Inc. - Toronto Terminals Railway - Transport Canada - VIA Rail Canada - UBCO School of Engineering - University of Ontario Institute of Technology - University of são paulo - University of Windsor - UOIT - WSP Canada Group Limited
2	- ABB - AECOM Canada Ltd - Ballard Power System - BC Hydro - Canadian National Railway - Canadian Pacific Railway - Cariboo Rail - Cummins - Dragados Canada - eCAMION - Environment and Climate Change of Canada - Infrastructure Ontario - Ministry of Jobs, Trade and Technology - National Research Council Canada - Natural Resources Canada - Ocean Sunrays Inc. - RHT RailHaul Technologies Inc. - Simon Fraser University - Southern Railway of British Columbia (Retired) - Spherical Aspects Solutions Inc - SRY Rail Link - Thales Groups - Tractive Power Corporation - University of British Columbia, Okanagan - University of Victoria - University of Calgary
3	- AECOM - Albright Strategic Counsel - County of Elgin - County of Oxford

	- Collins Aerospace - Concordia University - GIO RAIL HOLDINGS - GIO RMS Corporation - IBI Group - Infrastructure Ontario - Jacobs - Kirra Group - Metrolinx - OCAD University - Ontario Tech University - Oxford County - Queen's University - Railway Association of Canada - Thales - Toronto Terminals Railway - Transport Action Canada - Transport Canada - VIA Rail - University of Ontario Institute of Technology - University of Toronto - University of Waterloo - UOIT - Wasser Resources Inc.
4	- ABB - Bombardier - CAD MicroSolutions - Canadian National Railway - Carleton University - Centre de développement des composites du Québec - Conseil National de Recherche Canada - CNRC - Electrefy - Environment and Climate Change Canada - Gantrex - Genesee & Wyoming Canada Inc. - LTK Engineering Services - McGill University - McMaster University - Ontario Good Roads Association - ÖBB - Austrian Federal Railways - Parsons - Polytechnique Montreal - Queen's University - Ryerson University - Sector Group Stäubli Electrical Connectors - Technologies Proxybus Inc

	- Transport Canada - VIA Rail - UOIT

APPENDIX 2: TEMPLATE OF FOCUS GROUP SESSION 1A

Project Opportunity	**Title**					
	Budget ($)		**Length (Year)**		**TRL**	
Important Reasons	1.					
	2.					
Challenges	1. Etc.			1. Etc.		
Solutions	1. Etc.			1. Etc.		

APPENDIX 3: TEMPLATE OF FOCUS GROUP SESSIONS 1B, 2, 3, AND 4

Group #	**Category:**					
Technology Opportunity	Specific Technology					
	Potential Level of Resources		Time to Execute (Years)		Proposed TRL Advancement	
Essential Collaborators	1. Etc.					
Key Objectives/Opportunities for Outcomes (i.e. technical, economic, environmental)	1. Etc.					
Challenges to Technology Development/Launch	1. Etc.					
Solutions	1. Etc.					
Notes						

APPENDIX 4: CONSULTATION SESSION TECHNOLOGY THEME AREAS

Session 1B: Industry, Catenary Free Electrification Rail Facilities

Specific Technology

Participants in this group identified the potential implementation of a stationary/mobile energy storage integration with off-peak usage for grid management and electrification of catenary-free systems.

Time to Execute	Cost	Technology Readiness Level (TRL)
<3 years	$10 M–$20 M	7–9

Essential collaborators for this technology were identified as:

- Rail transit fleets, such as Metrolinx
- Battery and energy storage suppliers
- Hydrogen and electricity producers/utilities

Opportunities

Participants in this group identified several opportunities aligned with this technology. A technical and economic opportunity for commercialization exists in finding an application for energy storage technology in transportation, such as real-world transportation customer integration and driving technology. Developing this technology could also create wider business cases, thereby creating a pathway for other non-transportation and transportation applications.
Operationally, participants identified the technology as a means of saving money for rail users as it could involve selling power back to the grid. Another socioeconomic benefit identified includes the management of energy through “demand management” tools to reduce the cost of electricity, thereby leading to lower fares for passengers and making rail transportation more appealing, accessible, efficient and sustainable in the long term. Participants identified that, environmentally, this technology could lead to overall GHG reductions, presenting an environmental opportunity.

Challenges

Several challenges pertaining to the proposed technology were identified by participants in this group. The first is the possibility that transit agencies may face roadblocks when seeking funding from the public. In addition, developing the business case involving public funding can be elaborate and time consuming.

A second potential challenge identified is the uncertainty of electricity pricing and other inputs. Participants suggested that the uncertainty of these technical aspects are due to the fact that the ecosystem around this industry is not currently developed, and key components need to be established.

The final challenge identified by this group is that of public concern. There could be a perceived safety risk associated with current large-scale energy storage and an overall reluctance to implementing these solutions locally in communities.

Solutions

Participants in this group identified several solutions to these challenges. With regards to funding concerns, participants suggested that partners and collaborators need to reach out proactively to the right agencies to increase knowledge and confidence in proceeding with the project, and to ensure that the involved agencies have aligned strategies.

To potentially address cost uncertainty, participants identified setting up long-term contracts for power and electricity to establish the business case, and hedging contracts for maintenance, would address cost uncertainty.

To address public concerns, participants identified awareness or marketing campaigns that discuss environmental issues with a focus on the efficiency and positive environmental changes associated with electrified rail systems. Such campaigns could be facilitated by a trustworthy and credible non-governmental organization in the field of environmentalism with funding provided by all partners involved.

Session 1B: Industry, Hydrail Switching Yards

Specific Technology

Participants in this group identified hydrogen fuel for freight in switching yards as a proposed technology innovation for Canada. This could entail a three-phase approach. Phase one could include a front-end engineering study with output duty-cycle analysis, i.e. a feasibility analysis. Phase two could entail a demonstration project that retrofitted existing vehicles in the supply chain. The third phase could involve the commercial rollout of such hydrail cars in switchyards.

Time to Execute	Cost	TRL
3–4 years	Phase 1: $250K Phase 2: $50M Phase 3: TBD	7–8

Essential collaborators for this technology are identified as:

- Rail operators, such as CN, CP, etc.
- Manufacturers of hydrogen technology manufacturers (e.g. fuel cells)
- Hydrogen suppliers and distributors, electrolyser on site (local production)

- Transport Canada in the role of safety and regulatory support (adjustments to regulations) and collaboration at the federal level
- Provincial governments and ministries of energy and transportation (knowledge transfer for potential influence of regulations)
- Manufacturers for rolling stock
- Battery storage companies
- Consulting design work
- Academia and universities for highly qualified personnel (HQP) and allied research
- Colleges to ensure project-based training of technicians

Opportunities

Participants of this group identified several opportunities aligned with this technology, both environmental and economic. This project could reduce GHG emissions and contribute to the carbon economy by reducing rail operational expenses and reducing freight costs. These cleaner and quieter operations could present a carbon-neutral economically viable solution demonstrating Canadian technology for domestic export markets, thereby protecting and enhancing Canadian hydrogen innovation leadership. A possible commercial opportunity may exist for the operator to extend the overall lifecyle of the asset. For manufacturers, a commercial opportunity could be the development and commercialization of a product for market with export potential within North America.

A socio-environmental opportunity identified by the participants is the potential noise emissions reductions associated with alternative fuelled vehicles.

A potential technical opportunity identified is the learning and data compilation associated with the project, possibly leading to the application of the vehicles in large-scale applications such as main lines or long-haul freight.

Challenges

Three specific challenges pertaining to the suggested technology were identified by participants in this group. The first is that it is unclear what the “fuel of the future” will be. Participants brought forth the following acronym they felt pertained specifically to this challenge – “VUCA” (Volatility, Uncertainty, Complexity and Ambiguity). This translates into a difficulty for rail operators in determining today which technology – i.e. which energy system and vehicular application – will be applicable in 25 to 30 years.

The second challenge is the “just-in-time” structure of the North American economy, including the reliability of the service and the integrated nature of the manufacturing structure. The group also identified the existence of uncertainty in Canada pertaining to a lack of guided or strategically mandated targets for alternative fuels and energy to initiate or require deployments.

Solutions

Participants outlined several potential solutions to the challenges noted above. The first is identified as ambiguous political leadership in declaring transportation innovation as a strategic sector, which would encourage the government and the private sector to invest. The second is the possible creation of a federal fund for transportation innovation dedicated to promising new technologies. An example of a similar initiative provided by the group is the Electric Vehicle Infrastructure Demonstration (EVID) Program funded by Natural Resources Canada, which has spurred investment into charging systems for electrified vehicles (cars and buses).

Participants also identified the fact the rail network could act as a national mobilizer for other transportation deployments enabling a multiplier effect, which creates long-term strategic development opportunities for a national rail innovation network.

Session 1B: Industry/community, Hydrail Passenger

Specific Technology

Participants in this group suggested hydrail and hydrogen fuel for passenger and light-rail applications to grow into hydrogen energy systems. Participants envisioned this technology requiring three phases.

Time to Execute	Cost	TRL
Phase 1: Six months to launch, with an additional six months to build 6 kilometres of rail Phase 2: 18 months (potentially in tandem with phase 1) Phase 3: Two years	Phase 1: (6 kilometres, including retrofit and yard switcher) $45M Phase 2: (into the city) $55M Phase 3: C$250M Total: $350M	6 (integration piece) Phase 1: TRL 9

Essential collaborators for this technology are identified as:

- Penticton Indian Band
- Caribou Rail
- Southern Rail of BC
- K'ul Management Group
- SMARTer Growth Partnerships
- University of British Columbia (UBC)
- Aviaon Development
- H2 supplier, community (track site H2 station)
- Transport Canada, regulatory and safety side

Opportunities

Participants identified several opportunities associated with the suggested technology. The first being the creation of a collaborative national innovation hub for hydrail, with partnerships extending across Canada leading to an R&D cluster of innovation. This technology, according to participants, could provide ongoing innovations in reducing GHGs and connecting communities, leading to innovative exports of sustainable technology.

Participants identified commercialization and economic development of the hydrail retrofit kit could also lead to local growth and community-based economic opportunities. Additionally, the group

identified indigenous leadership and indigenous political opportunity as an outcome of the initiative, leading to an innovative export of human rights and social planning through rail technology innovation.

Challenges

In addition, the group suggested that identifying a minimal viable product, as well as funding to address both concerns, as another challenge.

Lag time to carry out mandates was presented as an allied challenge in the downloading of responsibilities to local communities. According to participants, there is a delayed political and social will, or institutional inertia, in government in general and this creates challenges for innovative and cutting-edge technology development.

Technologically, the group identified the need for a minimal viable product, as well as funding to address both concerns, as an ongoing challenge.

Another perceived challenge identified is that of expedited social licence or “not in my backyard” attitudes (NIMBYism).

Solutions

Participants identified a potential solution to these challenges to pave the way of implementing this technology. This could be through the resiliency that comes from connections to community-integrated projects built on strategic alliances and a “commonwealth” approach in consortium-based projects.

Other important aspects identified by this group include indigenous recognition and reconciliation demonstrated through respecting different approaches to developing communities, and recognizing the heterogeneity of indigenous communities and other local communities as core factors.

Ultimately, participants identified local factors and local leadership as core considerations to take into account in developing consent-based, co-developed and adaptive projects that find success in this technology area.

Session 1B: Government/academics, Hydrail Long Distance Freight

Specific Technology

The technology identified by this group is long-haul hydrail with high-quality emission reduction and decarbonizing freight. Participants described this technology in two phases. Phase one involves a demonstration project with a feasibility study of a hydrogen fuel tender that operates along freight distances carrying liquid hydrogen (LH2). Phase two is centred on technical issues associated with sourcing the fuel, while using LH2 and prototyping the tender.

Time to Execute	Cost	TRL
5 years	$20M–$100M	Start: 3–4 Prototype: 5–6

Essential collaborators for this technology are identified as:

- Tank car providers
- Rail operators
- Hydrogen fuel suppliers
- Fuel cell suppliers (for modifications to engines)
- Tender fuel suppliers
- Colleges and universities for feasibility studies
- Standards bodies (specifically, Canadian Standards Association (CSA) and the American Association of Railroads (AAR))
- Rail associations

Opportunities

Participants identified three primary opportunities that exist in alignment with the proposed technology. The first is a technical research and development opportunity, as phase two includes the development of a tender and the clustering of expertise knowledge around such technologies, which require the training of highly qualified personnel (HQP) to assist freight operators and to find a pathway toward de-risking the adoption of innovative technology.

The second opportunity is environmental, as the technology could lead to GHG reductions and shape the development lifecycle of tenders to enable faster integration of new engines that reduce air pollutants and other common air contaminants (CACs).

The last opportunity identified by this group is economic and commercial. This technology could be a test-bed for Hydrogenics and Ballard Power Systems in Canada. Canada needs to demonstrate market pull for these technologies in order to retain these global companies, and support their export potential and growth. This could attract other global companies into Canada.

Challenges

Participants of this group identified several challenges that prevent this technology from being deployed. Risk aversion specifically geared towards financial or technical aspects exists in general in the rail sector as well as local communities where these technologies would operate.

A lack of technology standardization, including codes and standards for hydrogen production, distribution, storage, utilization, and long-distance transportation creates an ongoing set of challenges for this technology. The lack of clear Canadian standards for hydrogen tender cars constitutes a barrier and it will take time to overcome through industry and public coordination.

Solutions

In response to these challenges, participants in this group identified several solutions. First, national policy drivers could be created that motivate innovation in this space, such as emissions targets for the rail sector (freight included) that require investment according to a given timeline. To de-risk implementations, academic researchers could be deployed over a multi-year period to conduct necessary technical analyses and feasibility studies for the industry and recommend near- and long-term policy solutions.

Government could assist overcoming these challenges by having Transport Canada align with innovation funding branches in other ministries. This ministerial mandate alignment could prioritize rail technologies and lead to faster rail innovation as a national resource, providing compliance with environmental agreements and policies and help to achieve the government's job-creation and technology innovation goals.

In response to concerns surrounding standards, participants identified piloting demonstrations as critical – pilot projects with real-world tenders would eventually lead to the development of the desired standards and motivate implementation by fleets.

Participants identified that the relevance to other transportation modes could be better highlighted as well as part of long-term business case development through cross-sectoral synergies with the energy and automotive sectors.

Session 2: Operators/ manufacturers, Artificial Intelligence Fleet Management

Specific Technology

Participants in this group identified potential technological opportunities associated with using data collection, information management and artificial intelligence (AI) to optimize existing large rail fleets with expected trickle-down effects on smaller fleets.

Time to Execute	Cost	TRL
< 5 years	$5M–$10M	7–8

Essential collaborators for this technology are identified as:

- Manufacturers specific to the rail industry
- Big data and AI consultants
- Rail associations (specifically, Railway Association of Canada (RAC) and the Association of American Railroads (AAR))

Opportunities

Participants of this group identified two primary opportunities associated with AI applied to rail optimization. The first is economic, as increased operational efficiencies equate to a cost reduction for fleet operators. The second is environmental, as GHG emissions are reduced through operational optimizations that reduce wasted energy and resources.

Challenges

Several challenges associated with AI in rail applications were identified by participants in this group. From a technical perspective, participants identified data collection, information management and AI as mechanisms by which rail systems could leapfrog the challenges associated with a lack of expertise at the corporate level today. These tools could also be leveraged to help train future HQP for the industry.

A financial challenge identified by this group is the lack of sufficient staff and resources at rail companies to invest in data-driven optimization initiatives.

Participants also identified cultural challenges within rail. The first being a potential lack of confidence within corporations with regards to data-driven technology solutions that run counter to pre-existing patterns of operation lead to stasis and internal cultural reluctance to innovate in the data domain.

Another cultural challenge identified is the general conservatism and slowness associated with technology integration in rail due to the capital intensity of the business overall.
Participants also identified the challenge of prioritizing energy efficiency over other operational needs; without punitive federal or other regulatory measures, achieving greater energy efficiency may create costs that are not offset by long-term financial benefits. Thus, the lack of regulatory requirements for energy efficiency in rail make it difficult to prioritize AI and other technologies that achieve those goals over and above more immediate operational needs.

Solutions

Participants identified several solutions to spur AI-driven innovation forward in rail applications. First, identifying supporting subject matter experts within surrounding industries, including academics and consultants, who could assist with the technical mapping of internal capacities at rail companies and support the assessment process forward would help to overcome internal resource constraints. External contractors could be hired to perform systems analyses to effectuate energy optimization objectives with performance guarantees using AI mechanisms. Academia could also be leveraged to support feasibility assessments and AI support solutions development by being provided with rail data under non-disclosure agreements.

Session 2: Manufacturers/technology integrators, Propulsion Technology Simulation Tool

Specific Technology

Participants in this group identified the development of a simulation tool that can determine the most suitable propulsion technology to achieve operational optimization in energy efficiency for freight transport.

Time to Execute	Cost	TRL
18 months	$3M	4–6, leading ultimately to a demonstration project at level 9

Essential collaborators for this technology are identified as:

- Technology consultants
- Universities for AI and traction
- “Boutique” AI and big data firms
- Larger data companies
- Rail operators
- Train integrator
- Traction suppliers

Opportunities

Participants identified several economic, environmental and geopolitical opportunities associated with this technology.

An economic opportunity exists in reducing transit agency or operator costs through energy efficiencies overall, as well as increased commercial profits through the deployment and sales of high-margin technology tools, such as a simulation tool that could increase Canada's competitive advantage in rail innovation globally.

Environmentally, the technology would help to reduce carbon emissions through improved energy efficiencies.

A geopolitical opportunity emerges in the reduction of Canada's dependency on fossil fuels, including imported fuel sources.

Challenges

Participants identified several cultural challenges – specifically, the lack of industrial leadership in strategizing and investing in data-driven strategic change and technology development in the rail sector in general and the rail sector's cultural risk-aversion to the adoption of new technologies, especially given implied inherent labour losses based on the elimination of some direct jobs currently based on inefficiencies inherent in the system.

Finally, participants identified challenges associated with competitive barriers to collaborative R&D in this area for developing a simulation tool. The development of multi-OEM consortium-based intellectual property (IP) is difficult to envision as a result.

Solutions

Participants identified several solutions. Government could take the lead to encourage measuring efficiency. This could include offering concomitant innovation funding to de-risk the feasibility assessment and modelling of propulsion systems and infrastructure. The implementation of such a program of initiatives would require a North America-wide effort given that freight networks operate cross-continentally and regulatory requirements in one jurisdiction should – ideally – be reflected in both. Two key signals and policy drivers that would drive forward investments into alternative propulsion modelling and simulation tools, as well as alternative fuel adoption, would be higher carbon costs, higher costs for fossil fuels, or punitive emissions regulations.

To address the lack of skills within rail systems to develop in-house simulation and modelling capabilities, participants recommended attracting young talent to the rail sector by increasing the public profile of the innovativeness of the rail sector, highlighting its digitization and its big data goals.

To address the challenge of developing and legitimating a multi-OEM simulation tool, participants recommended the tool should be developed, owned and operated by an independent neutral non-profit body could be created to develop, maintain and run the tool on behalf of industrial members of the non-profit.

Session 2: Academics, Compressed Natural Gas (CNG)/Hydrogen (H2) to Diesel Complementation

Specific Technology

Participants in this group identified the development of data-driven tools to optimize the incorporation of other propulsion technologies that complement diesel systems by integrating CNG and hydrogen in only those portions of a rail fleet that make most sense operationally, economically and from an overall systems perspective.

Time to Execute	Cost	TRL
5 years	Natural Gas Project $10M Hydrogen Project $10M Total: $20M	4–9

Essential collaborators for this technology are identified as:

- Clean engine manufacturers
- Rail operators
- Short line rail operators
- Regulators

Opportunities

Participants in this group identified three opportunities associated with this specific technology. An environmental opportunity exists in protecting the environment through emissions reduction. Operational opportunities emerge in the form of cost reductions through cost-effective system solutions. Global economic growth opportunities emerge for manufacturers that support the growth of Canadian manufacturers is the macro-economic opportunity.

Challenges

Two primary technical challenges were presented by participants in this group, the first being high initial technological risk due to the lack of evidence-based knowledge regarding CNG and hydrogen propulsion technologies in the rail sector. The second is due to a lack of technology demonstration projects globally that industry, researchers or academia can currently access or point to as comparative cases.

Presently, rail companies possess comprehensive data about their own operations. However, academia does not have access to this data, which makes it challenging to run experiments or conduct testing on Canadian systems. Participants in this group noted a lack of access to operational rail data to accurately assess life-cycle costs and social impacts associated with both old diesel systems and to compare them to those of new systems with regards to variables such as powertrain performance or degradation over time. Commercial, industrial and empirical data are not accessible globally nor accessible by Canadian researchers (i.e., academia).

Where commercial, industrial and empirical data are available to Canadian actors, they are typically not sufficiently "domestic" to instill confidence in Canadian decision-makers, i.e. they emanate from global case studies that locate rail fleets do not trust as reflective of local circumstances.

Solutions

Participants proposed several solutions to these challenges. First, the integration of researchers and Canadian academia in systems modelling for rail operators so as to measure the likely performance and life cycle costs during pilots of alternative fuels in tandem with diesel operations.

Participants also suggested using pilot projects to collect systematic data from pilot operations and vehicles to support the development and improvement of new propulsion technologies and more precise modelling tools that predict alternative propulsion performance. Pilots should be allocated to less mission-critical elements of the network – i.e. avoiding high-risk lines -- but still offer some public profile. Therefore, proposed pilot routes include tourist lines and/or short-lines (i.e. commuter-intensive, but low frequency) that possess backup power in case of system failure.

Session 2: Government, Rail Electrification

Specific Technology

Participants in this group proposed the electrification of rail for commuter applications through the development of energy management systems, inclusive of battery electric, hydrogen fuel-cell electric and hybrid propulsion systems, including feasibility analysis, road mapping and physics modelling.

Time to Execute	Cost	TRL
5 years	$10M	5–7

Opportunities

Participants identified two opportunities associated with this proposed technology. Economically, such technology could help to improve the efficiency of transit systems overall, enhancing mobility for transit riders as trains could potentially operate with less downtime due to increased efficiency per unit. Alternatively, trains could also operate with more riders, thereby limiting operating costs by reducing energy demands per passenger (or unit of freight).

In addition, potential operational efficiencies might accrue through energy recovery, energy storage and bi-directional energy flow back to the grid.

Participants in the group suggested that an environmental opportunity emerges in the improvement of local air quality because of a decrease of air pollutants from trains in communities, where people are living and riding.

Challenges

Participants identified several technical and business-related challenges, including the technical knowledge gap at transit agencies with regards to the capabilities of electrification technologies, a lack of business casing around systems deployment costs and long-term operational benefits, and a lack

of a bona fide decision-making tool (i.e., a simulation tool) that enables the assessment of various technology deployments to determine best options in given circumstances.
Additionally, participants identified environmental challenges in that rail operations constitute a small segment of the overall transportation emissions profile for Canada, and if funding were tied to carbon intensity, the rail sector may not benefit from such a marketplace in the future.

Solutions

Participants identifies a solution in the form of a consortium-led case study research and feasibility study with a set of collaborators organized to perform case study analysis to solve the technical knowledge gaps noted above. As transit agencies are often not ready to fund the development of a new tool themselves, government involvement in technology innovation funding through a non-profit would be requisite to create the tool in the first instance.

Additionally, regulatory incentives would need ot be created to motivate technology investment into rail emissions reductions given its small overall footprint in the emissions landscape; an effective incentive program would reward the reduction of local air contaminants and air pollutants based on a calculation of the local economic externalities (e.g. health care costs) saved through technology implementation.

Session 3: Academics, Toronto Union Station Flow and Capacity

Specific Technology

Participants in this group identified the need to optimize Toronto's Union Station rail corridor and station, including train flow into and out of Union Station and passenger flow through Union Station. This type of technological innovation assumes a continued or growing use by Metrolinx of the GO Transit network and the UP Express, growing VIA Rail usage of the station and growing ridership for the Toronto Transit Commission (TTC). Technological solutions to the non-optimized nature of Union Station includes using existing passenger simulation tools and developing new simulation tools to predictively model how to optimally move people through the station (from one train system to another) and how to (re)design certain aspects of the station to increase human flow.

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Time to Execute	Cost	TRL
2–3 years	Less than $1M	Starting: 3 Ending: 6

Essential collaborators for this technology are identified as:

- Rail operators (e.g., Metrolinx, VIA Rail and TTC)
- Facilities and public landowners
- Security services (i.e. policing)
- Research universities
- Mass movement and crowd analysis software providers

Opportunities

Participants identified several economic opportunities, including time and productivity improvements for the Greater Toronto Area if the operations of Union Station were to become more effective and efficient. Productivity efficiencies and time savings could be extended regionally and nationally as well, given that many national and inter-city networks, such as VIA Rail and Billy Bishop Airport utilize and converge upon Union Station.

Environmentally, participants identified energy efficiencies that could be maximized through the usage of multi-modal transit systems if Union's operations and movement flow patterns were improvement, including the reduction of "down-time" in operations and improved transit services to move more people across the same network.

Participants also identified technical opportunities that arise from leveraging, commercializing and monetizing software technologies to address user and rider capacity constraints that impact clientele and services for Metrolinx.

Challenges

Participants identified several challenges, including a lack of data collection and management by different sources at Union Station and their non-standardized formats. Data collected and used separately by VIA Rail, TTC, and Metrolinx create incompatibility issues because the parameters are non-comparable. From an analytical perspective, creating comparable parameters for modelling may prove to be technically and mathematically difficult. And from an empirical perspective, validating the modelling outputs using real-time data (such as a micro-agent simulations in a big system) may require disaggregated, personalized data inputs, which would create privacy concerns. The computational power required to properly analyze these data sets and all associated variables is also extension and would require partnership with major computing powerhouses.

Finally, the group identified challenges associated with gaining consensus and governance agreement across multiple stakeholders as to which priority recommendations should be pursued in data analysis if the challenges above could be overcome.

Solutions

Participants proposed several solutions, including the creation of a multi-stakeholder consortium initiative to ensure "buy-in" from all relevant actors. The given initiative could identify all rail and bus stakeholders that generate and own relevant data, and engage them to identify the type and mechanism of data collection and exchange needed in the initiative, and building consensus based on ongoing engagement in the analysis, data outputs and data flow inputs.

Within a confidentiality framework, stakeholder engagement could be furthered in the generation of new highly-valuable data sets such as Bluetooth and WIFI activities to capture information related to the movements of people, which may exist in disaggregated and identifiable forms. Thus, a non-profit

data trust could be developed as a neutral governance structure that collect, house, analyze and regulate the ongoing iterations of data collection and analysis on behalf of all stakeholders involved.

Session 4: Industry, Rail Car Demonstrator

Specific Technology

Participants in this group identified the development of a demonstrator rail car to assess differing materials in test environments and in situ. This demonstrator car would integrate not only steel composites or plastics but also other aspects of materials design innovation, including new manufacturing, validation, operability, and joining techniques, etc.

Time to Execute	Cost	TRL
6 years total 3 years for design 1.5 years for fabrication 1.5 years for validation	$50M–$100M	3–6/7

Essential collaborators for this technology are identified as:

- Railway operators
- Standards body
- Rail OEMs
- Heavy-duty coach and bus OEMs
- Parts manufacturers for transportation (Tier I–III suppliers)
- Materials suppliers of raw material such as additives, resins and fibres
- Universities and academics
- Testing centres/facilities

Opportunities

Participants in this group identified economic opportunities, including the fact development of this kind would create jobs and assist the manufacturing industry across Canada. The optimization of operations could lead to increased profit margins and it could support the cultivation of knowledge and capacity-building in innovative materials in Canada, thereby increasing the export potential of Canada-based supply chains, while leading to the development and adoption of new technologies in rail.

From an environmental perspective, materials advancements could support lighter vehicle designs, which would ultimately result in fewer emissions per vehicle and across entire rail networks over time.

Challenges

Participants identified three challenges, the first being that return on investments resulting from the initiative could be insufficient to motivate further investments into R&D, given that returns on research-based investments in rail typically have long gestation periods and immediate returns are unlikely.

Participants identified low volumes as a challenge; the fact procurement volume is generally low in the rail sector, i.e. in the hundreds per annum rather than millions per annum (as in the automotive sector), means less opportunity to innovate on a per vehicle basis. There is also less fragmentation among Tier I to III suppliers in the rail industry. Therefore, the low volumes and fewer suppliers with less internal market competition could delay the integration of new materials even if they are demonstrated as effective.

Solutions

Participants identified several solutions to the challenges noted above, including the development and launch of a non-profit technology consortium dedicated to supporting materials innovations that would support competitive manufacturers. This consortium of partners would enable industry-wide communications on materials innovation, similar to how the Consortium for Aerospace Research and Innovation in Canada (CARIC) and CUTRIC have been able to do in the aerospace and transit sectors, respectively.

The cluster would need to be structured on a "business-to-business" (B2B) framework for the eco-system to develop in the commercialization realm, rather than being academically-based and focused on early TRL research solely.

Participants also identified the enhancement and implementation of Canadian content regulations as policy measures that could support higher levels of risky technology innovation in materials, especially for publicly-funded rail vehicle procurements.

Participants identified a wholesale revamping of public procurements of rail systems to support systems-wide innovation more broadly, so that high-cost vehicles that integrate new materials could be justified based on lifecycle and long-term operational and system-wide savings.

Session 4: Industry, 3D Printing for Rail Parts

Specific Technology

Participants in this group identified the implementation of design principles and standards for three-dimensional (3D) printing of spare parts for fleet operator applications.

Time to Execute	Cost	TRL
5 years	$5M–10M	7–9

Essential collaborators for this technology are identified as:

- Railway operators
- Production agents (designers, manufacturers and sellers of 3D printed parts)
- 3D printer manufacturers and material experts (universities collaborating with industry)
- Validation regulators (testing facilities and standards bodies)
- Users and clients, e.g. fleet operators and OEMs

Opportunities

Participants identified two opportunities aligned with this technology. First, leadership in 3D printing for rail offers a global techno-economic opportunity that could enable the industry to transition into newer technologies and spearhead the development of a booming global industry, while simultaneously avoiding the high cost associated with non-action.

Second, rail operators could minimize their stored inventory and thus optimize their operations by reducing real-estate dedicated to stock parts. This could lead to cost cutting for taxpayer-funded transit services, increased profit margins for private and public transit operators, and increased asset usage by extending the life of the vehicle platforms.

Challenges

Participants identified several challenges pertaining to the risk associated with new 3D printed parts. Participants identified the fact the rail industry has strong risk aversion and an overt safety culture, wherein over-regulation often stifles innovation, but given the safety issues at hand, this over-regulation might not be eliminable easily.

As rail is a capital-intensive industry, participants also identified an innovation aversion related to the desire to avoid liability due to negative outcomes (e.g. operational down time) associated with 3D printed parts that may affect the safety of trains, tracks or networks.

Participants also identified a current lack of standards for 3D printed parts, as standards development requires pilot projects and pilots in the rail sector are still considered “too risky” to brand images to countenance.

Solutions

Participants in this group proposed several solutions to these challenges. To potentially solve risk aversion concerns, a low-risk pilot program in which failures would not have a great impact on brand or public perception of rail safety could be identified. This could allow for seemingly “risky” technologies to be cultivated within safe settings, such as test-beds and test tracks. This could also build expertise and confidence within the sector to move to higher-risk products and higher-risk pilots in the future.

To address the lack of standards, participants identified the need for phase one of this intiativie to use existing standards and build upon existing standards to improve them or identify standards gaps in a second phase.

Session 4: Academics, Hybrid Light-weight Structure

Specific Technology

Participants in this group identified the need for a demonstration car demonstrating, specifically, hybrid light-weight structures that use multi-materials and which encompasses all aspects extending from development to certification.[2]

[2] This technology theme area is similar to the initiative proposed by Group 1, Session 4, documented earlier in this report.

Time to Execute	Cost	TRL
5 years	$10M	3–6

Essential collaborators for this technology are identified as:

- Manufacturers of composite materials and integrators (e.g. Tier I to II suppliers in the aerospace industry)
- OEMs and end users
- Material suppliers
- Subject matter experts in academia

Opportunities

Participants in this group identified several opportunities aligned with this technology, including environmental benefits given that lighter rail cars could lead to reduced fuel consumption and reduced emissions. From the economic perspective, participants identified the fact reduced fuel consumption could lead to operational cost reductions and an increase in rail asset service life, which would reduce the need for long-term maintenance.

Participants identified techno-economic benefits in the form of Canadian leadership in this rail sector, which would lead to job creation through increased technical competency in a globally relevant sector.

Challenges

Participants identified several challenges pertaining to the suggested technology including technical challenges. Where regulation codes do exist, they restrict innovation, but the complete absence of standards also makes it difficult to commercialize new technologies. The rail sector needs to find a balance between the two. In the case of new materials, there is an absence of inspection technologies to help develop new applications.

New materials technologies also create the challenge that they require recycling, repair and maintenance until the end of their life-cylces – and the recycling, repair and maintenance of new materials is unknown territory for both academics and commercial actors.

Participants also identified a labour gap in that recruiting skilled talent to develop this technology is challenging, as the technology is not deemed attractive enough to lure in researchers and HQPs at Canada's universities today.

Solutions

Participants outlined several potential solutions to the challenges noted above, including the fact subject matter experts that specialize in failure modes and standards can be identified as part of a regulatory body and standards development team. Rather than employing volunteers, standards developers could be incentivised to participate, which would motivate and drive standards development more rapidly in the new materials space.

Participants also identified a public relations solution in that the rail industry must begin presenting itself as futuristic, and technologically and socially diverse to enhance uptake of interest and research among new HQPs.

Session 4: Academics, Sandwiched Sheet Polymers Testing and Development

Specific Technology

Participants in this group identified a technology that uses aluminum and sandwiched sheet polymers, which requires further testing, designing and manufacturing assessment. This initiative would require three phases: phase one encompasses a global landscape survey of existing technology feasibility and applicability across different modes; phase two tests weaknesses in design principals and technologies and creates updates to address those weaknesses; phase three includes manufacturing using the optimized design and processes cultivated in phase one and two.

Time to Execute	Cost	TRL
5 years	$5M–$10M	3–6

Essential collaborators for this technology are identified as:

- Clients of the product (OEMs)
- End-users
- Manufacturers
- Material suppliers
- Academia and experts in mechanical and corrosion engineering
- Standards and regulatory bodies

Opportunities

Participants identified two opportunities associated with this proposed technology, including the development of a new product which could lead to overall emissions reduction from the vehicular structure of rail systems, as well as the potential for long-term Canadian jobs growth in a globally relevant transportation innovation field, given that new materials are relevant to modes of transport beyond rail itself (e.g. automotive, aerospace, etc).

Challenges

Participants identified several challenges that hinder this technological innovation, including specifically the fact that rail assets have long lifespans, and this longevity presents a barrier to inserting new innovations in pre-existing vehicles that have decades more of “life” to them. The long life-spans of rail assets slow the pace of innovation in Canada. Thus, there is a current lack of interest in upgrading vehicular technologies.

Participants also identified a potential lack of political will especially towards Canada’s Paris commitments, resulting in an absence of punitive measures for polluting or over-emitting technology providers or transportation operators – thus avoiding a natural incentive that could motivate action towards innovation if pollution or energy inefficiencies were priced.

Solutions

Participants identified several solutions to overcome the challenges noted above, including a reassessment of refurbishment cycles for rail cars. Newer materials could be introduced into long life-space vehicles during refurbishment cycles at mid-life, and they could be inserted as requirements or preferences in new public tenders for vehicles being purchased today (which will also exist for decades hereafter). Progressively stricter standards focusing on innovation in succeeding vehicle platform models for emissions or operational savings could spur the adoption and integration of advanced materials designs.

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