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Hydrogen: An Overview

Eastern Canada

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The Transition Accelerator
L'Accélérateur de transition

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ABOUT THE TRANSITION ACCELERATOR

The Transition Accelerator (The Accelerator) is a pan-Canadian charity that creates positive, transformational system changes that solve societal challenges while moving Canada down viable pathways to reach net-zero greenhouse gas emissions by 2050. To achieve this, The Accelerator harnesses existing economic, social and technological disruptions already affecting multiple sectors and regions. Using momentum already underway, it acts as a catalyst and convenes innovators, progressive industry, researchers and other key groups into **collaborative teams that advance Canada down credible, compelling and capable pathways to a stronger, net-zero future.** Our current priorities are Canada's hydrogen economy, electric vehicle market penetration, building decarbonization and electrification and grid integration.

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Daniel Hoornweg is an Associate Professor, Associate Dean and the Richard Marceau Chair at Ontario Tech University. Following almost 20 years with the World Bank, including as Lead Advisor overseeing Sustainable Cities and Climate Change programs, he returned to Canada, and was Chief Safety and Risk Officer for the Province of Ontario from 2012 to 2020 (Technical Standards and Safety Authority).

Dan's academic background includes degrees in Earth Sciences from the University of Waterloo, a Masters in Environmental Engineering from the University of Guelph and a PhD in Civil (Sustainability) Engineering from the University of Toronto. Dan researches energy and material flows of cities and urban systems. He became a Fellow with the Transition Accelerator in 2020.

David Wotten BEng, CPHD
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David Wotten is an Energy Systems Engineer and researcher for Ontario Tech University in the fields of high-performance building technologies, carbon emissions and hydrogen technologies. He also has 20 years of International Business Development experience working with companies ranging from start-ups to multi-billion dollar corporations.

David is passionate about the environment and the reduction of carbon emissions. His research has shown that carbon emissions can be reduced by over 80% through building design and implementation of existing technologies while improving comfort and quality of indoor living. David is also an Internationally Certified Passive House Designer.

Dick Kauling PEng
KAULING SOLUTIONS

After 20 years as Engineering Manager for Alternative Fuels at General Motors, Dick retired in 2014. He established his consulting company KauliNG Solutions and now lives in Coburg, Ont. His areas of expertise include Next Generation alternative fueled automotive technology; design, development and production execution of NG (Next Generation) automotive technology; core knowledge in OEM light-duty product design and execution involving natural gas (compressed natural gas – CNG), liquefied petroleum gas (LPG - Autogas), and hydrogen fueled technology for transportation; and, associated national and international codes, standards and regulations for safety and environmental compliance.

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Ofelia Jianu is an Assistant Professor of Mechanical Engineering at the University of Windsor. She works on heat, mass and momentum transport with application to alternative fuels and energy conversion systems. She has over 40 publications in reputable journal and conference papers in the subject. She is the recipient of the Canadian Foundation for Innovation John R. Evans Leader's Fund. With her team she investigates phase transitions and transport phenomena with the goal of identifying local irreversibilities, which are detrimental to the performance of sustainable energy systems. The research in I-FuEL benefits Canada's efforts in reducing greenhouse gas emissions and supports economic growth of clean technology and its commercialization opportunities.

Ehsan Armouldi MASc Candidate

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Ehsan Armouldi is a graduate research assistant and MASc candidate at the Department of Mechanical, Automotive, and Materials Engineering of the University of Windsor. His specialty is in thermofields, energy conversion, and computational fluid mechanics with a focus on heat exchangers design and energy systems. He has a patent in the field of solar measuring instruments and five peer-reviewed published papers in accredited journals, national and international conferences.

FOREWORD

This three-part report focuses on hydrogen applications in Eastern Canada – progress and prospects.

SECTION 1: **BUSINESS — HYDROGEN BUSINESS SURVEY RESULTS (EASTERN CANADA)**
Section 1, by David Wotten, summarizes activities in the more than 50 businesses primarily focused on hydrogen in Eastern Canada (Ontario, Quebec, New Brunswick, Nova Scotia, Prince Edward Island, Newfoundland and Labrador).

SECTION 2: **RESEARCH — INVESTIGATING HYDROGEN ENERGY-ORIENTED RESEARCH BY UNIVERSITIES OF ONTARIO, QUEBEC AND THE MARITIMES**
Section 2, by Ofelia Jianu with Ehsan Armouldi and Mudit Nijhawan, summarizes more than 200 hydrogen-focused research papers published since 2014 by about 50 researchers at 23 universities across eastern Canada.

SECTION 3: **TRANSPORTATION — A REVIEW OF HYDROGEN AS A TRANSPORTATION FUEL**
Section 3, by Dick Kauling, provides a detailed analysis of the next steps needed to shift a significant share (>10%) of the heavy-duty trucking fleet (Class 8) to hydrogen fuel along the Windsor-to-Montreal highway corridor.

Hydrogen is experiencing a resurgence in the research community and public discourse as its critical role in the shift to a low-carbon economy becomes clearer. Various jurisdictional goals such as 'net-zero carbon by 2050' (as largely ascribed by the Paris Agreement) can not realistically be met without the widespread application of hydrogen as an energy carrier. Within the last year, for example, in Canada there have been more than 100 webinars on hydrogen (and more than 100 times that many globally). Key reports published or updated in 2020 include hydrogen strategies for Canada, Alberta, Ontario, European Union and the U.S.

> Hydrogen is experiencing a re-surgency in the research community and public discourse as its critical role in the shift to a low-carbon economy becomes clearer.

> With so much new information entering the hydrogen discourse, this report strives to not be 'yet one more', but rather, hopefully, supports a process of pragmatic, yet rapid, development of the sector.

With so much new information entering the hydrogen discourse, this report strives to not be 'yet one more', but rather, hopefully, supports a process of pragmatic, yet rapid, development of the sector (in full support of the goal to move toward a low-carbon economy, if not net-zero, by 2050). With that in mind, three main recommendations, or 'next-steps' accompany this report.

1. The Ontario Hydrogen Business Council held an online conference 'Hydrogen Sustainability and Finance' November 19/20, 2020. This was the best attended event of its kind in eastern Canada. **The event should be repeated annually and a business report** (like the one provided here in **SECTION 1**) **should be updated and made available** for open access on the HBC website. This is likely the easiest way to provide and ongoing business directory of 'who's doing what in hydrogen'. Similar initiatives should be held in French (Quebec focus) and for western Canada.
2. **SECTION 2** of this report contains a list of active researchers and hydrogen research projects in eastern Canadian universities. The list is already out of date. **The list should be augmented with the accompanying paper hydrogen energy related research and development efforts in Canada**: A perspective by Karaca and Dincer, 2020.[1] In speaking to Canadian researchers a paper of this type needs to be published every 3 to 5 years for at least the next decade to reflect the rapidly growing nature of hydrogen research in Canada.
3. **SECTION 3** of this report provides a detailed assessment of technical and regulatory requirements to start shifting HD freight transportation to hydrogen fuel (replacing diesel) starting with the Highway 401 corridor. **This work should be augmented with the recent paper Macro-Level optimization of hydrogen infrastructure and supply chain for zero-emission vehicles on a Canadian corridor** by Shamsi et al 2021.[2] This report, along with several other researchers and policy documents suggests that a key priority for hydrogen development in eastern Canada is additional generation, provision of strategic fuelling stations, and incentivizing the freight industry to shift from diesel fuel to hydrogen.

1 From "Special Issue: Sustainable Energy and Green Technologies", by W. Chen and W. Chong, (Ed). *International Journal of Energy Research*, Vol. 44, Issue 12, pp. 9246 – 9253, 2020.

2 From "Macro-Level optimization of hydrogen infrastructure and supply chain for zero-emission vehicles on a Canadian corridor", by H. Shamsi, et al. *Journal of Cleaner Production*, Vol. 289, 2021.

EXECUTIVE SUMMARY

Thirty-six hydrogen-focused businesses identified through industry discussions, were surveyed for their perspectives on opportunities, challenges and progress in expanding the 'hydrogen economy'. Fifteen of these companies provided detailed discussions on their current operations. Detailed responses and a company brief of all 36 firms are provided in **SECTION 1**.

Responses from the surveyed businesses are illustrative. For example, a respondent identified how Norway's shift to hydrogen-powered coastal ferries is driving global market development. More than 100 new vessels are sought over the next ten years. Norway has a population of 5.3 million and an economy of about $403 billion. The coastline length is similar to North America's Great Lakes, about 17,000 km. Yet the Great Lakes Region has a population of 78 million and an economy over $4 trillion. Similar market potential in heavy duty trucking was identified by survey respondents.

Business respondents reflected a sense of optimism and even excitement in the potential for hydrogen business development. Although international markets were identifies, for example with Norway's hydrogen powered ferries, however the industry is still Canada-focused: 71% of suppliers and 62% of customers are Canadian.

The majority of business respondents are pursuing electrolysis as main means of hydrogen generation. With regard to hydrogen, Eastern Canadian businesses surveyed focus on power generation, transportation, and steel and chemical production. Businesses surveyed suggest the current cost premium for hydrogen is 20% (over higher carbon energy alternatives) and identified funding support and market information and consensus as key priorities.

Hydrogen research in Eastern Canada is flourishing. **SECTION 2** outlines active research programs in hydrogen production (25 research institutions), storage (16 institutions), and hydrogen utilization (13 institutions). Summaries are provided for 204 research papers. As yet there is no institutional grouping or coordination on hydrogen research, similar to the University Network of Excellence in Nuclear Engineering (UNENE) which is a Canadian-based alliance of universities, nuclear power utilities, research and regulatory agencies.

> There are about 183,000 heavy-duty trucks, tractors and trailers in Canada.

There are about 183,000 heavy-duty trucks, tractors and trailers in Canada. Ownership is widespread, many operators working with one, maybe two trucks. Yet as outlined in **SECTION 3**, changing the fleet is relatively straightforward as the top 10 and top 100 companies operate 20,500 and 42,500 tractors (Class 8) respectively. Of the top 100 trucking companies, 45 are headquartered in Ontario and 27 in Quebec. Ontario roads support more than $1.2 trillion in the movement of goods annually. The crossings at Windsor, Sarnia and Fort Erie/Niagara Falls handle 59% of all Canada-U.S. trade. Shifting Canada's transportation sector needs be anchored in the Windsor-Montreal corridor.

Two critical 'next step' assessments urgently needed to support the shift to a hydrogen economy are:

i) a review of integrated mobility in the Great Lakes Region; and
ii) updating Canada's overall energy strategy.

Any effort to promote hydrogen fuel use for freight transport along the Windsor to Montreal corridor should take advantage of several 'stars aligning'. Both the Government of Canada and the new Biden-administration (with Pete Buttigieg, former Mayor of South Bend, ID and now Secretary of Transportation) are calling for 'transformational infrastructure' to shift economies toward low-carbon and post-pandemic growth. Support is growing for a carbon-free Montreal to Chicago corridor.[3] The application of hydrogen to support highway freight transport can readily be applied to a new system of low-carbon buses (likely hydrogen) that could dramatically change transportation (and economic) patterns across the region. Decarbonizing and enhancing mobility in southern Ontario (and across the Great Lakes Region) is the best way to enhance overall sustainability.[4] As the Gordie Howe International Bridge proceeds toward opening in 2024 a strong case can be made that decarbonizing transportation (with hydrogen) in the Great Lakes Region should be a top priority for Canada and the U.S. and the 500+ governments and utilities that make up the Great Lakes mega-region.

In June 2012, the Canadian Academy of Engineering, with support of Alberta Innovates and The Bowman Centre (Sarnia, Ont.), published *Canada: Winning as a Sustainable Energy Superpower* (Volume I and II) and *Canada: Making the Case for Nation-Building Projects*[5] (see the May 25, 2012 eight-page Globe & Mail summary). These reports should be updated considering:

1. Paris Agreement and push for 'net-zero carbon' by 2050;
2. COVID-19 pandemic;
3. economic shifts especially in Alberta;
4. recent change in Administration of U.S. Presidency;
5. experience gained from Canada's response to COVID-19, and
6. the potential that hydrogen has to disrupt Canada's overall energy system.

3 From Environmental Energy Institute. (Producer). (2020). Carbon Free Transportation Corridor, CLEEN2040 [Webinar]. https://www.environmentalenergyinstitute.com/carbon-free-corridor

4 From Cities and Sustainability: A New Approach, by D. Hoornweg, 2016, New York: Routledge.

5 From The Canadian Academy of Engineering. (n.d.). *Canada: Winning as a Sustainable Energy Superpower.* Accessed, July 6, 2021.

The COVID-19 response may serve as a dress-rehearsal for Canada's shift to a low-carbon economy.

Canada's history with energy falls into two broad categories. First, Canada applied large-scale civil engineering projects for the generation of electricity. This started with the blessings of geography and the massive flow of the Niagara River (hydro-electric generation made possible through a riparian-sharing agreement with the US) and the unique constitutional structure of Canada, giving unprecedented provincial authority over energy. British Columbia and Quebec, along with Newfoundland (Churchill Falls) followed, each creating a provincially owned utility (usually the largest corporation in the province). Ontario ran out of the 'blessing of geography' for relatively easy hydro-project development and therefore, with federal government support, built some of the world's largest nuclear power plants.

Electricity makes up less than a third of Canada's overall energy use however in most provinces it assumes a disproportionately large role in energy policy (e.g. Ontario's last 112-page Long Term Energy Plan has less than two pages devoted to non-electricity energy). In these provinces the price of electricity is typically the most debated campaign issue.

In Alberta, energy and the 'blessings' of geography take centre stage as well, however this is not through electricity, but rather oil and gas deposits. Alberta's (and Saskatchewan and Newfoundland to a lessor extent) energy focus has been petroleum production and sale outside provincial borders. Massive transitions are underway.

Canada's progress to-date in combating the COVID-19 pandemic does not bode well. In vaccines, for example, the finger-pointing between the federal government (vaccine procurement) and the provinces (vaccine distribution, health care, schools and business 'lock-downs') intensifies.

The COVID-19 response may serve as a dress-rehearsal for Canada's shift to a low-carbon economy. Trouble seems to be looming, and hydrogen may well be the catalyst that either further tears the Canadian fabric or helps energize an era of cooperation. Hydrogen has a unique ability to disrupt all energy systems including oil and gas production and the price (and carbon intensity) of electricity. By 2050 the role of hydrogen in Canada's overall energy system will look very different if energy programs are optimized by province rather than the greatest good for the country (and possibly the world). Without a clear and well-discussed national energy program, there is a good chance that sub-optimum solutions will be advocated by individual provinces or corporations.

SECTION 1

Hydrogen Business Survey Results

EASTERN CANADA

Section 1 — Hydrogen Business Survey Results

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1 HYDROGEN BUSINESS SURVEY RESULTS

EASTERN CANADA

1.1 Abstract

Atmospheric CO_2 emissions continue to rise every year at about 3 ppm despite calls to keep planetary temperature increases below the 2.0°C (aspirational, below 1.5°C). Canada committed to this goal through the Paris Accord.[1] Hydrogen (H_2) could help to reduce CO_2 emissions and support Canada's transition to a low carbon economy. Hydrogen technology has been developed, pilot projects built, hydrogen (H_2) buses demonstrated, and transition pathways analyzed, yet the hydrogen (H_2) economy has little widespread adoption. This study analyzes hydrogen businesses in eastern Canada to establish the state of the hydrogen economy. A survey was conducted with an analysis of each company. The results suggest a solid foundation of companies that can provide core components to build the foundation of a hydrogen economy. The industrial base can design, produce and install the infrastructure needed to produce, store and use the hydrogen in various pathways. The major barriers are funding (cost of hydrogen), consumer awareness and government policy. The industry provides effective greenhouse gas (GHG). The low-carbon nature of hydrogen and the energy storage capabilities of hydrogen presents opportunities in freight transportation (heavy truck and rail) and seasonal energy storage.

1.2 Introduction

Beneficial features of hydrogen include its simplicity; one proton and one electron making it the most common and abundant element in the universe. Up to 90% of the universe is composed of hydrogen [**1**]. Hydrogen is very energy dense by mass containing 120MJ/kg compared to gasoline at 45.8 MJ/kg [**2**] and it is the most energy dense element by weight. Volumetrically, however hydrogen is very energy light, containing 8MJ/L compared to gasoline at 32MJ/L [**3**]. Pure hydrogen can be created through electrolysis of water with a 'waste product' of oxygen. Hydrogen can be stored as compressed gas, liquified, or combined with other elements. Hydrogen can be converted back to useful energy through a fuel cell with water as the only product. This hydrogen cycle can be powered by renewable energies like, wind, solar and hydro making it relatively carbon free.

1 Canada committed to reduce emissions by 30% below the 2005 level of 732 megatonnes of CO_2 by 2030 (and a long-term agreement of 80% below the 2005 level by 2050). Each Canadian, on average, was responsible for 22.7 tonnes CO_2 in 2005; the Government of Canada committed to reduce this to 12.5 tonnes per person in 2030 and just 3.3 tonnes per person in 2050. More recently Canada committed to be 'net-zero' by 2050. Roughly, atmospheric carbon dioxide emissions need to stay below 450 ppm to keep temperature increase below 1.5°C; 550 ppm below 2°C.

There are many hydrogen strategies and plans published outlining the transition to a hydrogen economy [4]. There are demonstration projects of various technologies and a healthy hydrogen industry [5]. Looking at the strategies, the demonstration projects and the established hydrogen industry, why is the hydrogen economy not more visible? There is an aspect of the current hydrogen economy that is not consistent with the transition to a low carbon economy. In 2019 the global production of hydrogen contributed 830 Mt of atmospheric CO_2 [6]. These emissions are greater than all of Canada's.

This report surveys companies in the hydrogen sector in eastern Canada and determines the state of the industry from a business perspective. The survey focuses on costs, carbon emissions and readiness to market. Questions regarding barriers and growth potential highlight areas and or technologies that can be removed or expanded to accelerate the transition to a low carbon economy.

1.3 Methods

Data for this report was gathered through two methods. Research was conducted on each company independently through publicly available resources (e.g., websites, published journals, news media, and annual reports). Companies were also sent a survey with very specific questions regarding their involvement in the hydrogen economy. The questions and results of the survey are provided in the Survey Results & Data section below.

1.4 Survey Results and Data

1.4.1 Types of Businesses and Business Activity

FIGURE 1.1 Organizations and the hydrogen economy

What is your organizations' connection to the hydrogen economy? Check all that apply.

15 RESPONSES

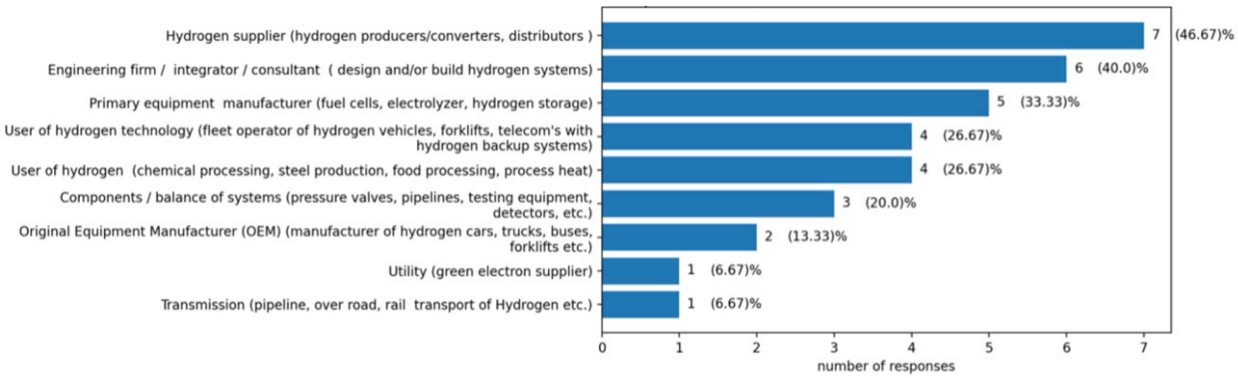


FIGURE 1.2 Hydrogen economy involvement

What areas of the hydrogen economy is your organization involved in? Check all that apply.

14 RESPONSES

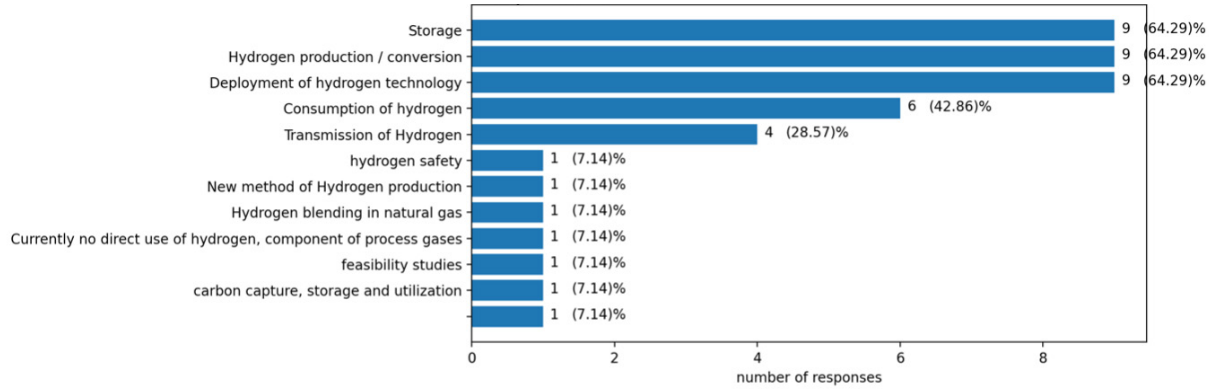


FIGURE 1.3 Hydrogen production/conversion types

What type of hydrogen production/conversion are you involved in? Check all that apply.

14 RESPONSES

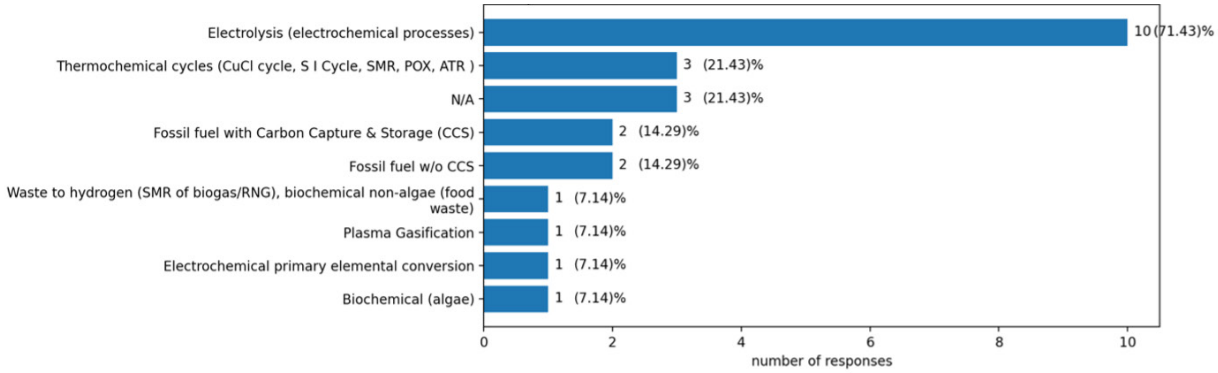


FIGURE 1.4 Hydrogen storage types

What type of hydrogen storage are you involved in? Check all that apply.

14 RESPONSES

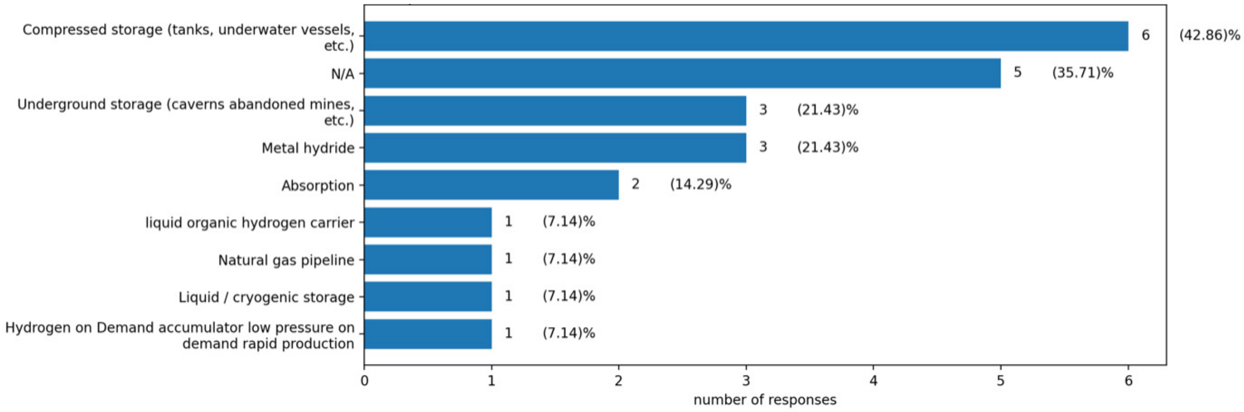


FIGURE 1.5 Hydrogen consumption uses

What is the consumption of hydrogen used for? Check all that apply.

15 RESPONSES

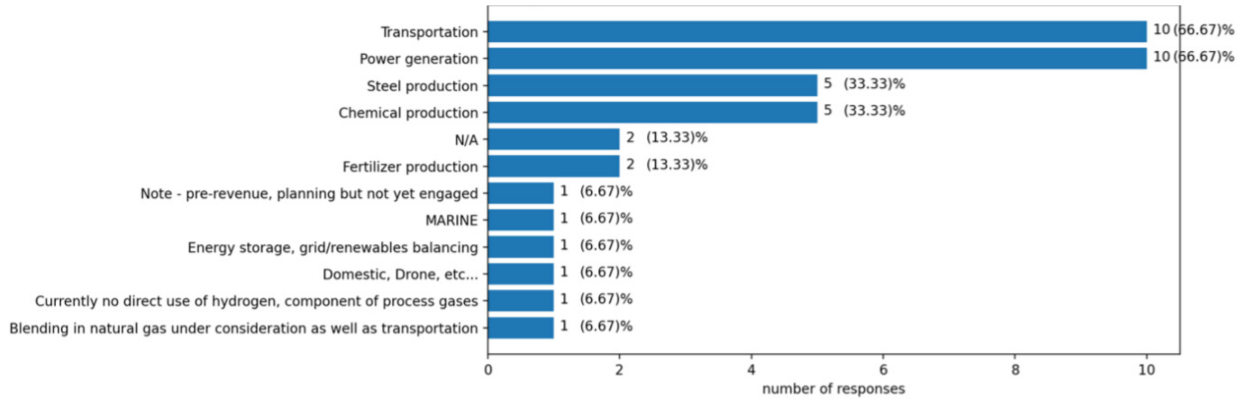


FIGURE 1.6 Hydrogen deployment

In what areas do you deploy hydrogen technology? Check all that apply.

15 RESPONSES

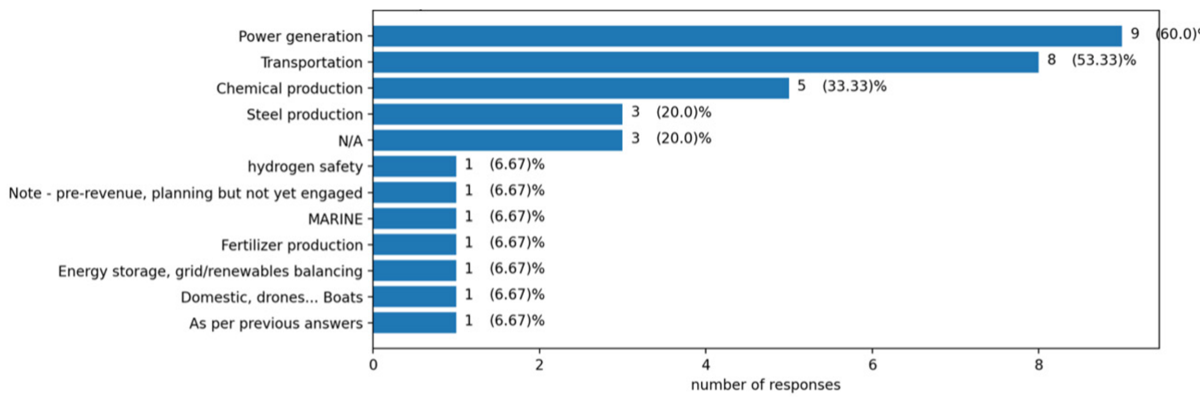


FIGURE 1.7 Hydrogen applications

What hydrogen applications is your organization involved in? Check all that apply.

15 RESPONSES

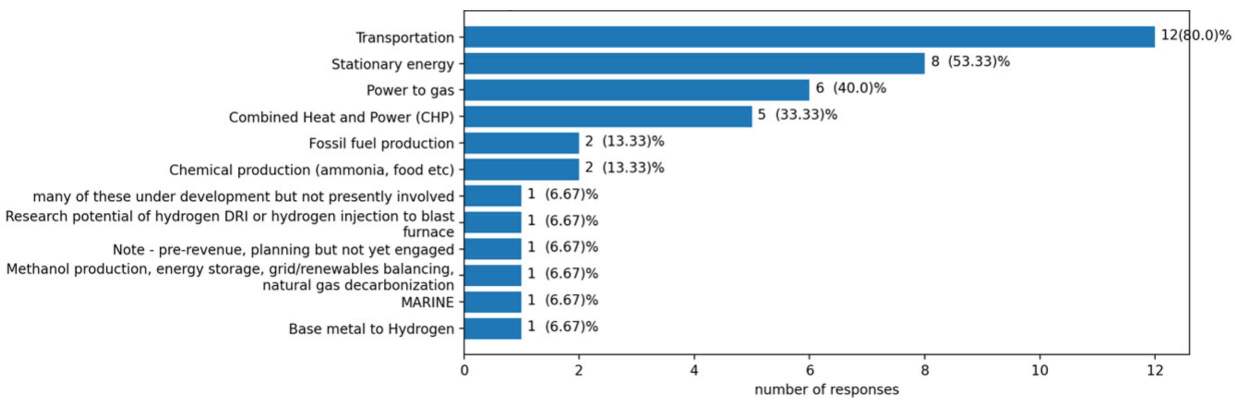


FIGURE 1.8 Transportation applications

What type of transportation application are you involved in? Check all that apply.

15 RESPONSES

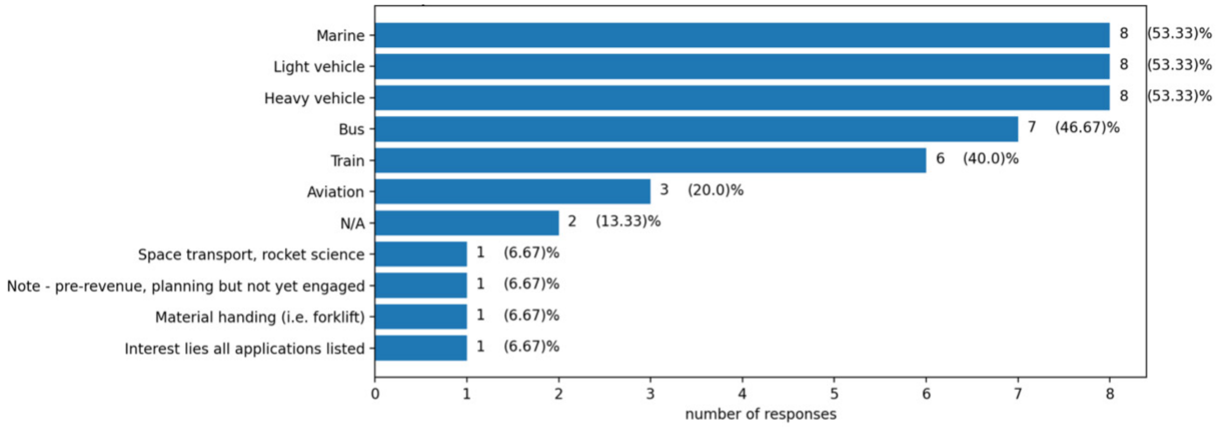


FIGURE 1.9 Stationary energy

What type of stationary energy are you involved in? Check all that apply.

15 RESPONSES

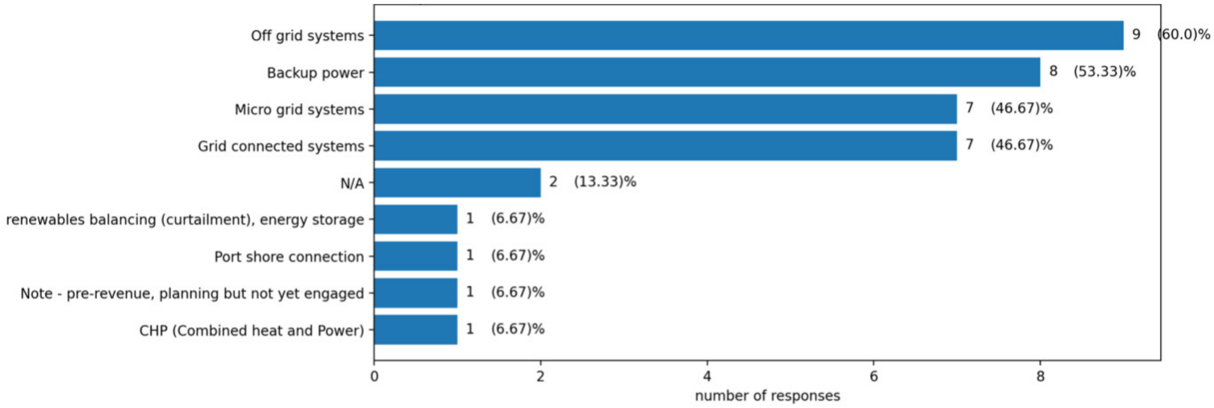


FIGURE 1.10 Power to gas

What type of power to gas are you involved in? Check all that apply.

13 RESPONSES

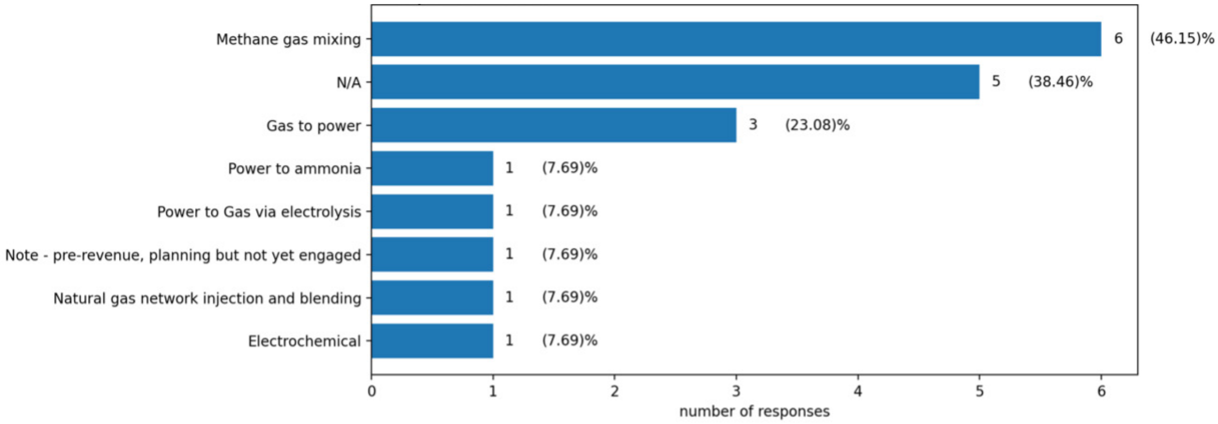
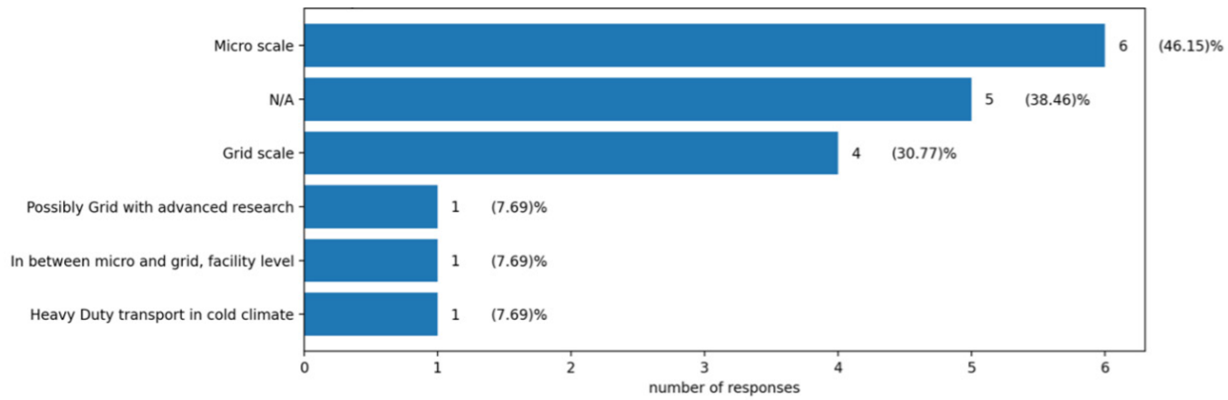


FIGURE 1.11 Combined heat and power (CHP)

What type of combined heat and power (CHP) are you involved in? Check all that apply.

13 RESPONSES



1.5 Costs

FIGURE 1.12 Cost of hydrogen production at lower heat value

Cost of hydrogen production $/kWh (CDN$) at lower heat value LHV of 1kg = 33.33kWh

11 RESPONSES

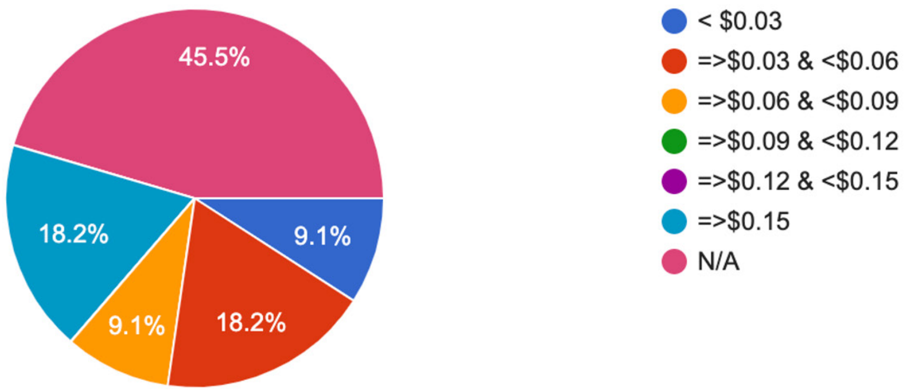


FIGURE 1.13 Cost of hydrogen storage at lower heat value

Cost of hydrogen storage $/kWh (CDN$) at lower heat value LHV of 1kg = 33.33kWh

10 RESPONSES

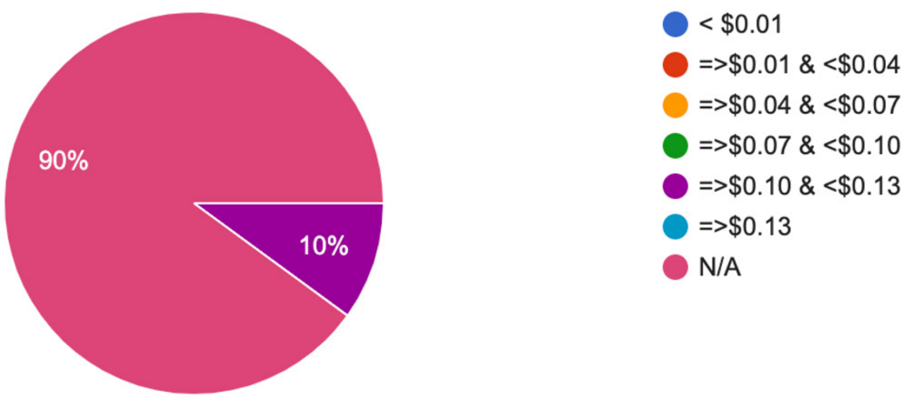


FIGURE 1.14 Cost of hydrogen distribution at lower heat value

Cost of hydrogen distribution $/kWh (CDN$) at lower heat value (LHV) of 1kg = 33.33 kWh

10 RESPONSES

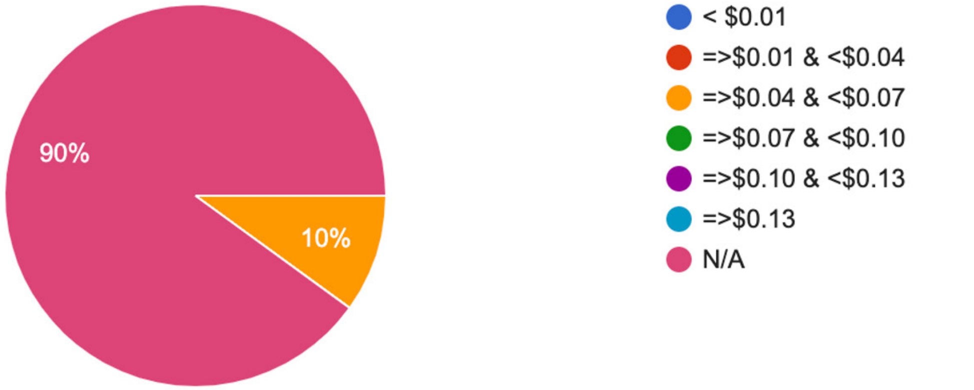
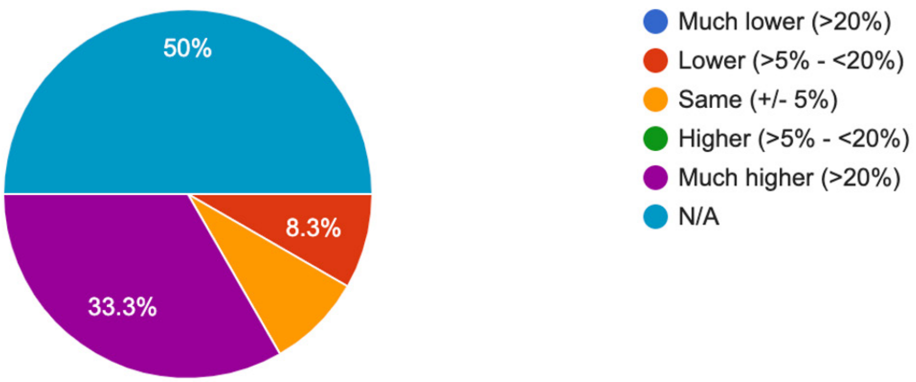


FIGURE 1.15 Cost of hydrogen vs current energy source

What is the cost of hydrogen versus current energy source for your application?

12 RESPONSES



1.5.1 CO_2 implications

FIGURE 1.16 Greenhouse gas (GHG) reduction factor

What is the greenhouse gas (GHG) reduction factor—kg of CO_2 reduced per kg of H_2 ($kgCO_2/kgH_2$) —used in your application? (i.e. replacing natural gas industrial heat with H_2 has an approximate reduction factor of 7 $kgCO_2/kgH_2$ when combusted in its place)

9 RESPONSES

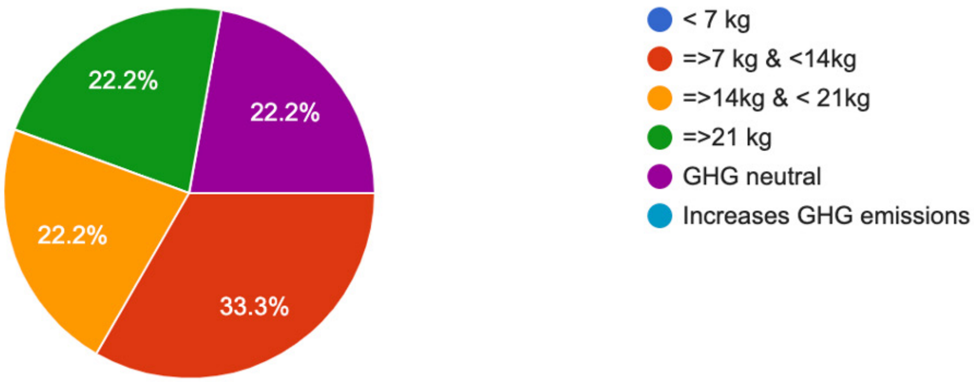


FIGURE 1.17 Payback period for reduced carbon to offset embodied carbon

What is your payback period, in years, for reduced carbon to offset embodied carbon of product/application/system?

8 RESPONSES

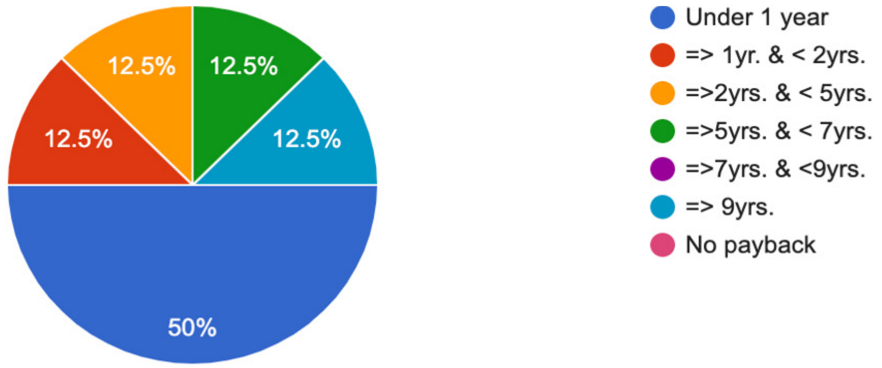
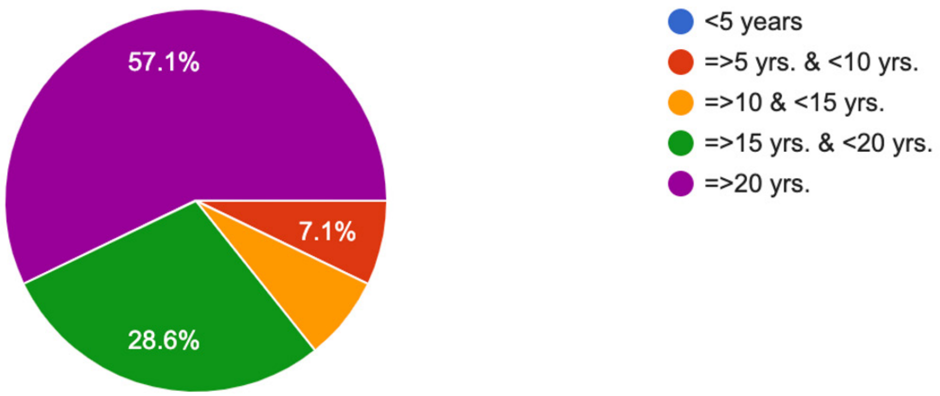


FIGURE 1.18 Hydrogen product/application/system lifespan

What is the approximate life span of hydrogen product/application/system under normal operating conditions?

14 RESPONSES



1.5.2 Markets

FIGURE 1.19 Customer location

Where are the majority of your customers located?

13 RESPONSES

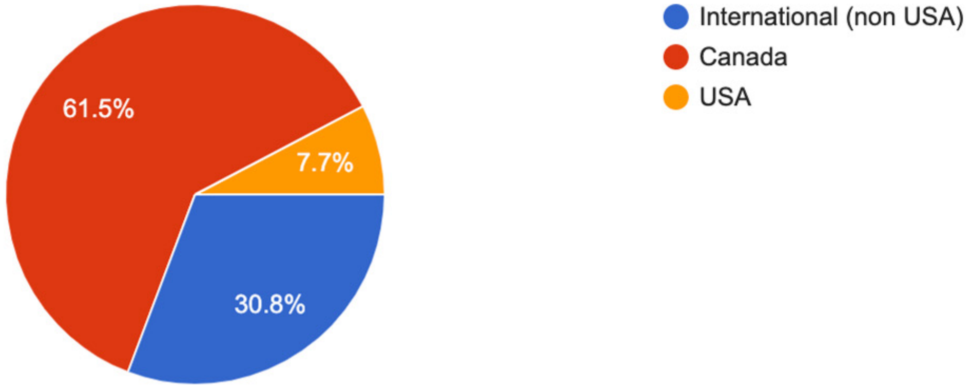


FIGURE 1.20 Supplier location

Where are the majority of your suppliers located?

14 RESPONSES

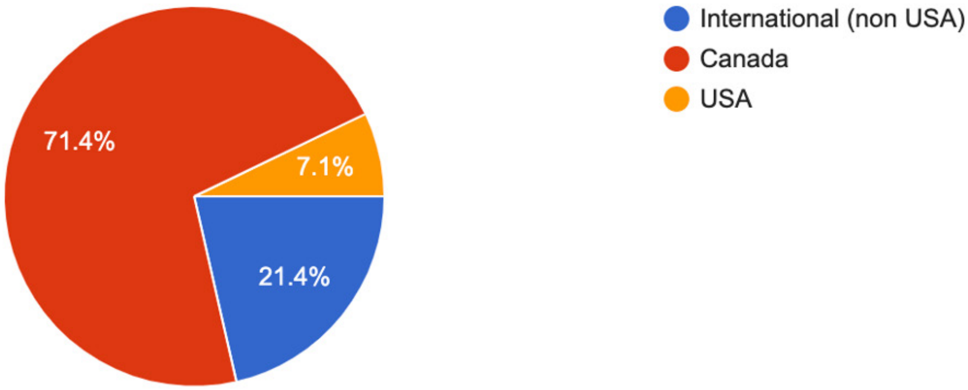
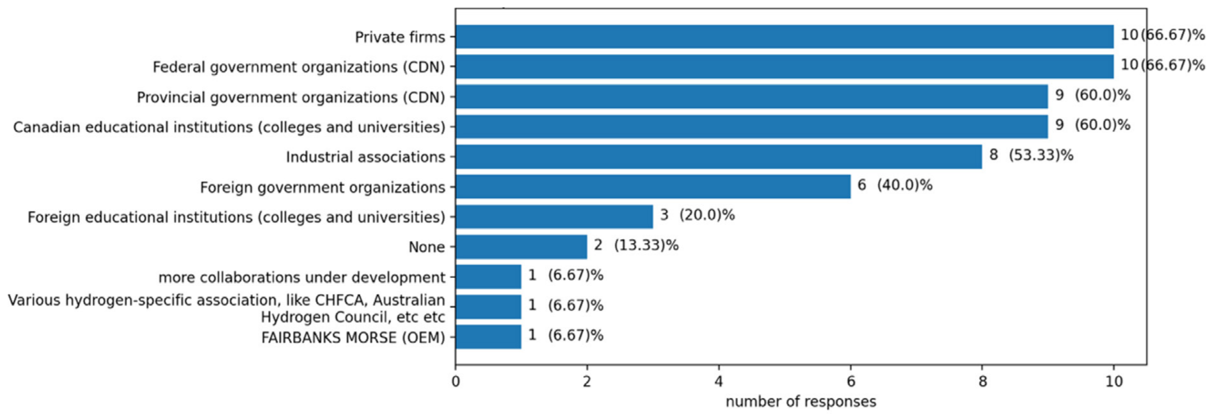


FIGURE 1.21 Hydrogen product/service providers

What organizations do you collaborate/work with to develop hydrogen products or services?

15 RESPONSES



1.5.3 Market Opportunities and Barriers

FIGURE 1.22 Market capabilities from hydrogen

Does your hydrogen product or service offer new capabilities to the market?

15 RESPONSES

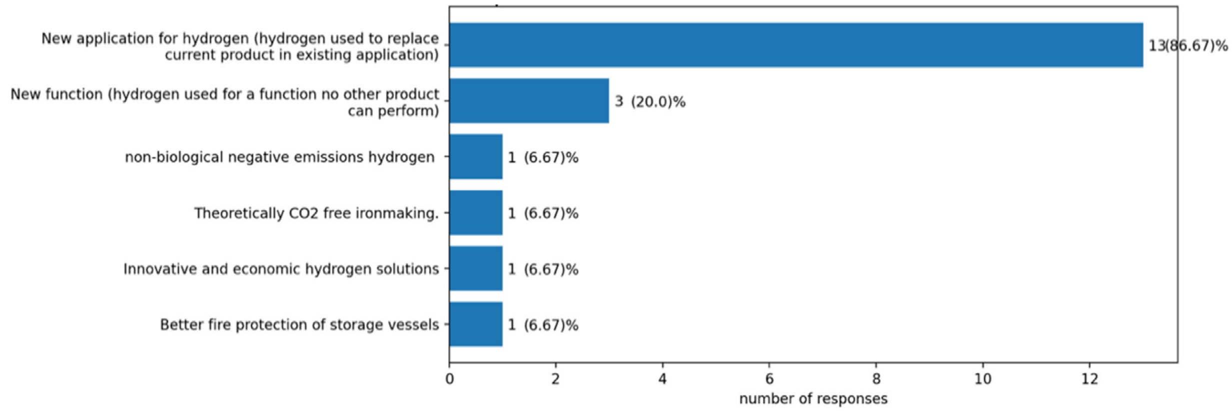


FIGURE 1.23 Examples of market capabilities from hydrogen

What new capability does your hydrogen product offer to the market?

Large scale modular extreme duty fuel system for high powered mobility - mining, marine, heavy trucks. Designed to marine standards for leading RATED efficiency.
On Demand Hydrogen allows for very little infrastructure requirements. Reduction of capital enormously. Rapid distribution of technology using existing distribution channels (Amazon, Couriers).
Post-pandemic technology to reduce mortality rate of COVID-19.
Faster recharge and more autonomy of heavy-duty electric vehicles.
We provide the cleanest hydrogen on earth with a carbon intensity of -333 gCO_2/MJ in which the cost of production can be heavily offset by the value of carbon credits.
Similar capability with zero emissions.
GHG free production of H_2.
The ability to reduce carbon in the natural gas grid.
New uses and applications of hydrogen in traditional industries like waste management, wastewater, food and agriculture (all private and public clients).
New biomass conversion technology for Power to X.

FIGURE 1.24 Stage of commercialization

At what stage of product/system commercialization are you for your major/primary/main product or system?

15 RESPONSES

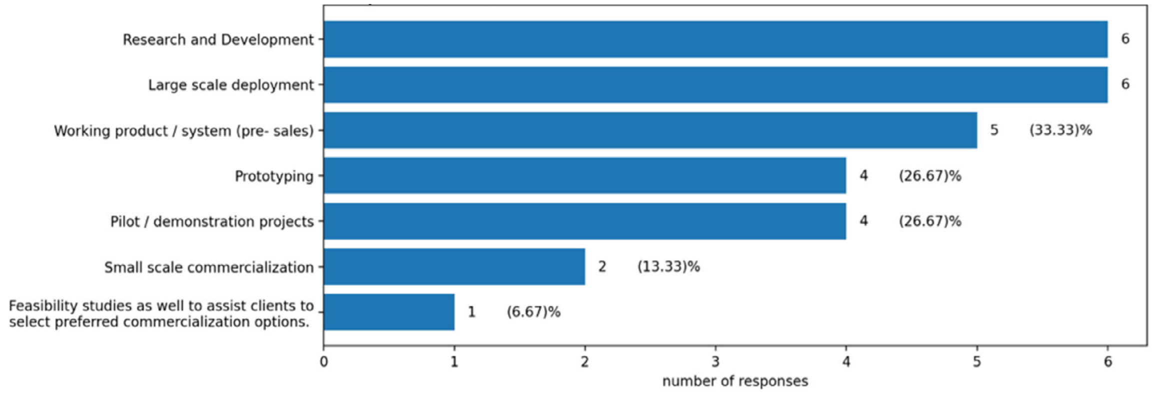


FIGURE 1.25 Advancement needs

What is needed to move your product/system to the next stage?

Goal to develop exportable technology but need a Canada-based project first in order to establish necessary credibility to participate in major international opportunities. 2) Policies must be put in place with carrots, sticks, and regulations to encourage the commercial deployment of hydrogen and fuel cells until the price of H2 falls to sub-parity with fossil fuels.
Manufacturing systems to process our consumable technology.
Funding.
More meaningful carbon-pricing, cost-sharing by governments, curtailment of all fossil-fuels tax breaks and incentives, reduction in the cost of hydrogen compression.
Further investment, completion of ocean-focused research project and basic engineering for pilot plant.
Our electrolysers are commercially available; we are eager to make Canada the next country with a large-scale implementation, which is predicated on large scale demand for H_2 and a positive business case that can involve regulatory support/incentives/stimulus.
Further collaboration with global organization research teams on various hydrogen projects. An understanding of the potential marketplace in Canada to identify costs associated with hydrogen, if it were available for purchase as a commodity.
Hydrogen fuelling infrastructure required for the deployment of FCEVs.
Funding, commercial partner, hydrogen infrastructure, economics.
Offtake and dedicated power tariff.
Industry confidence, favourable pricing for electricity, government assistance.
Certification of product.
Investment funds—Lots of exciting projects under-planning, need funds, sustainability stimulus funding, carbon credit markets, etc. to support these projects financially.
Demo project .

FIGURE 1.26 Barriers to deployment

What are the barriers to mass deployment of hydrogen technologies?

15 RESPONSES

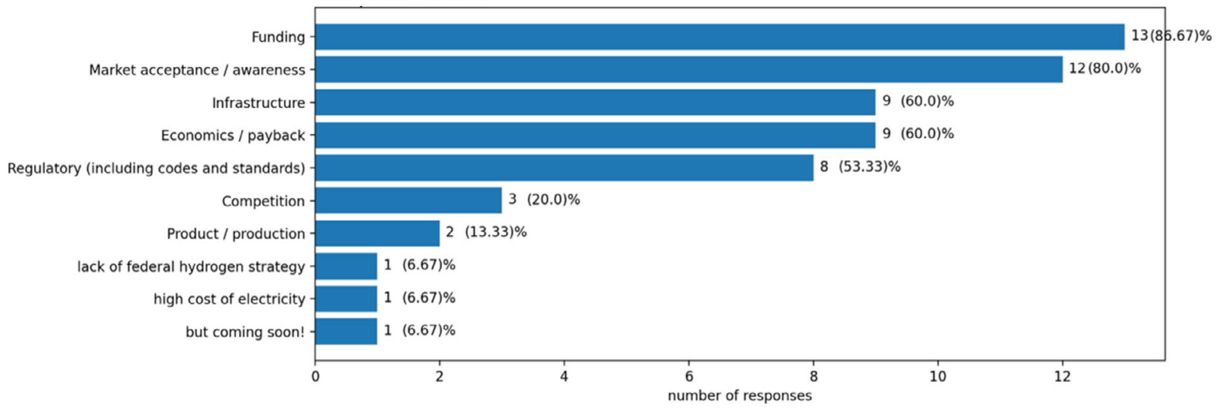


FIGURE 1.27 Examples of barriers and proposed solutions

What is the most significant barrier and what should be done to remove to reduce it?

Lack of policy to promote H_2. Without policy, H_2 adoption is voluntary and purely aspirational. Need strong, simple subsidy & penalty model (e.g. direct carbon tax to H_2 funding), and regulations (e.g. mandate improvement in Transport Canada fleet emissions) to promote H_2 adoption. Note that small pilot programs, demos, with short operating periods are the usual output of Canadian limited funding. I do not believe these are effective at really pushing the industry forward.
Allow us to demonstrate the technology!
Funding makes it less difficult to qualify.
Production cost per kg H_2, principally cost of compressing to 700 bars for transport applications.
A network of hydrogen pipelines would radically improve adoption, the CFS will help as well.
Offtake - Demand for hydrogen must be established in order for production to take root at a large scale.
A large-scale source of CO_2 free (or low CO_2) hydrogen is required that is economically viable.
Hydrogen fuelling infrastructure required for the deployment of FCEVs.
Hydrogen infrastructure; public acceptance and government funding and support.
Large subsidies on the OpEx and not on CapEx. Key driver is the power price and a dedicated low tariff is mandatory in regards to the potential of CO_2 emission reduction
Reduction in the cost of electricity is paramount as it accounts for close to 80% of production cost of green hydrogen by electrolysis. Likewise, confidence in the fledgling renewable hydrogen market is critical to allow others such as transit agencies and heavy-duty transport to move away from diesel and make the investment with sound economics.
Government support for P3 projects, provide funding etc. Carbon markets incentives for reducing emissions.
Clear regulatory framework and green hydrogen incentives.

FIGURE 1.28 Deployment acceleration

Which of the following areas would accelerate the mass deployment of hydrogen technologies?

15 RESPONSES

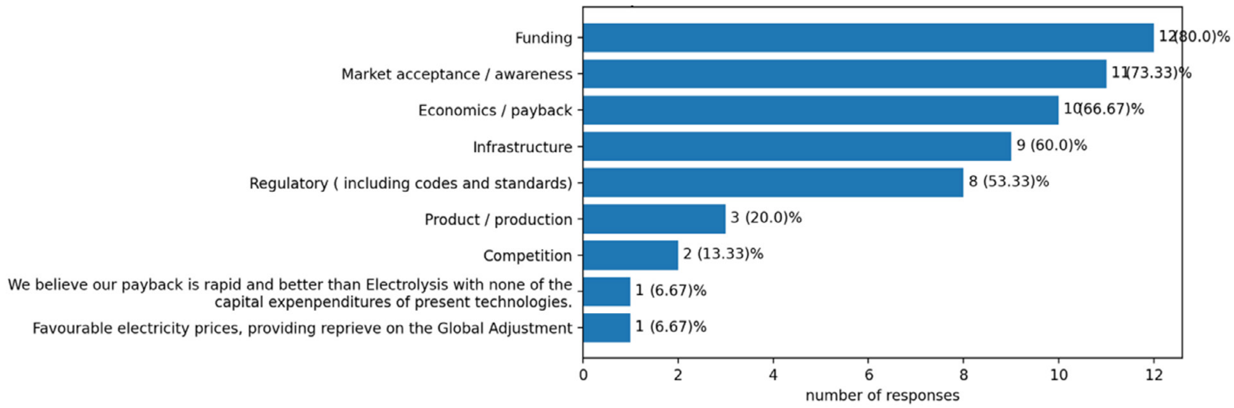


FIGURE 1.29 Specific actions to accelerate deployment

What is the most significant action that can be taken to accelerate the mass deployment of hydrogen?

Make hydrogen available for projects at a price attractive to operators; and not just in Montreal and Vancouver.
Available government funding.
Enable policies and programs that would make H_2 transition "cost-neutral" to customers for the first five years (until market forces take hold on their own).
Deploy and re-purpose pipelines, increase the value of carbon reduction in our economy through regulation and fuel standards.
Government support of the economics, from either the market demand side (subsidize the price for some applications e.g. P2G or mobility), or regulations that make hydrogen attractive (e.g. CFS).
Hydrogen strategy document for Canada outlining how funding can be directed to link potential suppliers and consumers.
Identification of high-volume hydrogen users (i.e. transportation, buildings, industry).
Indicate hydrogen infrastructure will be available (like battery chargers are presently available) set up refilling stations and encourage purchase of cars and companies to use hydrogen powered trucks and buses.
Regulation: implementing a CO_2 tax to make green hydrogen competitive or deciding huge CO_2 emission targets should open up the market completely.
Reduction in the cost of electricity would allow companies to realize a more competitive and compelling economic model to compete.
Government support for P3 projects, provide funding etc. Carbon markets incentives for reducing emissions.
Clear regulatory framework and green hydrogen incentives.

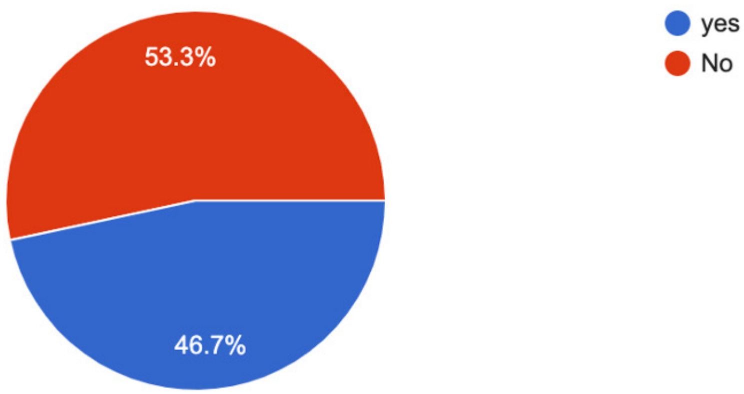
FIGURE 1.30 Hydrogen economy opportunities

What is the largest opportunity for the hydrogen economy?

For us, it is the Norwegian coastal ferry renewal strategy. Well over 100 vessels will be replaced over the next 10 years with zero emissions technology.
Successful R & D will allow for fossil fuels to be converted to hydrogen with no GHG component. In other words, we believe our future technology will be able to convert fossil fuel to hydrogen and capture all carbon, not CO_2, but carbon through de-sublimation.
To be a post pandemic technology in reducing pollution in the world's hot spots of pollution as they are the same hot spots for COVID-19. This enables hydrogen to contribute to reducing both cases and deaths of COVID-19.
Complete displacement of fossil fuels, the largest economic sector (larger than internet, telecom and IT combined).
Replacing natural gas within our economy.
To decarbonize industry by offsetting SMR; mobility.
Utilize Canadian natural resources to become an energy exporter akin to natural gas markets.
Meeting GHG reduction targets.
Production of clean H_2 to replace the millions of tonnes produced annually by steam methane reforming; needs to be economical as SMR is inexpensive
Transportation to be green at large scale (maritime, trucks, etc.)
Reduction in GHG and Carbon emissions to enable Canada to meet climate targets
Vehicles is the obvious one, but transportation of the hydrogen to the fuelling station appears to be overlooked.
Decarbonization of hard-to-decarbonize sectors: heating, transportation, industry.
Power to X and intensive long-distance ground mobility

FIGURE 1.31 Stimulus funding

Has or will your organization apply for stimulus funding from the federal government? (Y/N)
15 RESPONSES



1.6 Survey Discussion

1.6.1 Types of Businesses and Business Activity

Companies were asked questions concerning their role in the hydrogen economy and specifics in functions and applications. Most of the respondents fall into three categories: Hydrogen suppliers, manufactures of hydrogen equipment and engineering firms / integrators of hydrogen systems. The area that they are most involved in are storage, production of H_2, deployment of H_2 technology and consumption of H_2. The most common storage technology used is compressed H_2 with some underground and metal hydride storage, while the production of H_2 is mainly through electrolysis. The deployment of H_2 technology is in the power generation, transportation, chemical production and in steel manufacturing sectors.

The applications and hence most of the consumption of H_2 are in the transportation, stationary energy production, power to gas and combined heat and power sectors. Transportation is focused on the marine, heavy vehicle, light vehicle, bus and train segments. Stationary energy production activity is diverse and includes off-grid, backup power supply, micro grids and grid connected systems. The power to gas activity is geared to methane gas mixing and gas to power applications. The combined heat and power systems are focused on the micro-scale size.

The survey indicates that there are businesses providing the core competencies in H_2 production, storage and applications to support the foundation of a functional hydrogen economy. The business applications have a high correlation with the 12 end pathways in the 2019 Hydrogen Pathways report published by the Canadian Government [4]. There are some interesting hydrogen production technologies that are in R&D stages at various companies that are not electrolysis outlined in the company brief appendix.

1.6.2 Costs

Production of Hydrogen ranges from under $0.03/kWh to over $0.15/kWh with some responses indicating an approximate cost of $0.06/kWh or $2.00/kg on lower heat value (LHV). There were very few responses on the cost of storage and distribution, but the indicated costs are between $0.10/kWh and $0.13/kWh and $0.04/kWh and $0.07/kWh respectively. In addition to the production, storage and distribution of H_2 the efficiencies of the applications must be factored and, given the high loss to heat in fuel cells, it can significantly increase the final cost. On a cost competitiveness with current technology most respondents indicated that the hydrogen solution is more than 20% more expensive, where applicable.

The more than 20% premium on H_2 replacements could be a hurdle for a H_2 transition pathway to a low carbon economy. Distinctive functionality over current and other developing technologies could mitigate the cost concern. In heavy freight transportation H_2 storage systems, energy density, and efficiency may offer longer range capability over existing and emerging technologies [7]. In stationary power, H_2 seasonal storage capability and future reduction in cost could make it the lowest cost solution [8].

1.6.3 CO_2 Implications

The production and use of H_2 can be a low carbon process but may not be depending on the production method. Global production of H_2 in 2019 resulted in 830Mt of CO_2e emissions [6]. This is a very important factor in the transition to a low carbon economy. The applications that the hydrogen is applied to also can make a significant difference to the overall reduction. If large emission sources are changed over to low emission hydrogen then more carbon is offset per kg of H_2 used, this is referred to as the GHG reduction factor measured in kg CO_2/kgH_2. The higher the reduction factor the more effective the application of hydrogen. The reduction factors ranged from 7 kg CO_2/kgH_2 to over 21 kg CO_2/kgH_2

Half of the respondents indicated that the carbon payback of the hydrogen applications was less than one year and 87% were less than seven years. This payback period is very important to making immediate reductions in GHG as indicated by the Intergovernmental Panel on Climate Change (IPCC) statement that dramatic measures need to be taken by 2030 to keep global temperatures from rising more than 1.5^{o}C. [9]. Most respondents indicate that the life span of their systems are over 20 years making the saving a long-term.

1.6.4 Markets

The location of most suppliers and customers are located in Canada with the next largest segment being international non-U.S. based. This geographic breakdown is favourable for economic growth within Canada as well as the growth potential for exports of hydrogen and hydrogen technology. A strong hydrogen industry can facilitate deployment of H_2 technology nationally facilitating reductions in GHG emission. The collaboration in the industry appears high with many firms partnering with industrial organizations as well as several levels of government and educational institutions.

Market Opportunities and Barriers

The respondents overwhelmingly indicated that their products and systems offer some new application for hydrogen that replaces a current product in an application. A number of respondents indicate that their advantage is in reduced if not negative carbon emissions.

The business readiness to deploy H_2 technology is mixed with less than half indicating that they are in large scale deployment and many more small-scale commercialization to working prototypes and R&D work. The consensus on how to move to the next stage with product and systems is to have a system that will level the market with fossil fuels and provide funding that can be used for things like demonstration projects.

The two largest market barriers seem to be funding and market acceptance and awareness. Following closely behind are infrastructure, economics/payback and regulations.

The most significant action that can be taken to accelerate the mass deployment of hydrogen according to the respondents are infrastructure support and financial support or policy change that would give credit for the carbon reduction of a hydrogen economy and make the fossil fuel alternative less affordable in comparison.

The biggest opportunity for hydrogen is its potential to replace fossil fuels, and specifically natural gas, and reduce our GHG emissions. There is an opportunity to convert Canadian natural gas to hydrogen by removing the carbon from it and therefore utilizing our natural resources without the GHG emissions. The other opportunity for hydrogen is for its use as a transportation fuel.

The survey indicates that almost half the respondents will be or have applied for stimulus funding from the Federal Government.

1.7 Conclusion

The hydrogen business sector in eastern Canada has the core competencies to provide the necessary components to support a hydrogen economy. The industry's dominant method of hydrogen production is through electrolysis and the most common storage method is in gas compression. The pathways for hydrogen consumption are more diverse and spread across 4 major sectors, power generation, transportation, steel production and chemical production.

The cost of the hydrogen solution is more than 20% higher than the existing technology that it is trying to replace. The cost consequences may be diminished by focusing on the storage capabilities of hydrogen and future reduction of cost through technology advancements.

Hydrogen production through electrolysis and various applications has a high reduction factor of CO_2 reduced per kg of H_2 consumed. Applications have a relatively short payback of embodied carbon. This factor is favourable in the need for immediate action in the reduction of CO_2 to meet 2030 climate change targets.

The two largest barriers to the hydrogen economy are funding and market awareness. Hence, what is needed to accelerate the hydrogen economy is funding, and favourable policy. One of the biggest opportunities of the hydrogen economy is its ability to replace natural gas and reduce CO_2 emissions.

It should be noted that 47% of the companies identified in the eastern Canadian H_2 economy study responded to the survey. The number of responses might have been influenced by the fact that this survey was being conducted in the spring of 2020 during the COVID-19 outbreak. To improve the accuracy of the results It would be recommended that the study be conducted again after the pandemic is over with the goal of a higher participation rate.

1.8 Company Briefs

These are brief company overviews by function including location, their involvement in the hydrogen industry and projects.

1.8.1 Manufacturers of Hydrogen Production and Fuel Cell Systems

GEMA SCIENCES [SURVEY COMPLETED]
5 FURBACHER LANE UNIT 4
AURORA, ON L4G 6W2

GEMA Science is in development of technology to produce hydrogen using benign abundant components that do not emit greenhouse gases, use electricity or heat. Cost of hydrogen today is $3.50US/kg target price of $2.50US/kg [**10**].

Also developing heatless methane reforming and other fuel cell components.

Hy2gen CANADA [SURVEY COMPLETED]
2000 MCGILL COLLEGE AVENUE
MONTREAL, QC H3A 3H3

Hy2gen Canada is a subsidiary of Hy2gen Germany and has an initial target of 1,500 tons of green hydrogen per month. They are developing projects across the country.

Green hydrogen produced by Hy2gen AG by means of Alkaline electrolysis or polymer electrolyte membrane (PEM) [**11**].

They located in Canada due to the central and local governments commitments to reducing greenhouse gases and the provinces of Quebec's ability to supply 100% green energy [**11**].

Projects:

- EMERY: At Varennes, an 86 MW electrolysis production plant for H_2 and O2as feedstock for a production of bio-fuels. ***Start of production in 2022.***
- GIBSON: At Varennes, a 120 MW electrolysis production plant for H_2 and bio-methanol for mobility sector and bio-methane for international markets. ***Start of production in 2022.***
- KAZALLON: At East Montreal, 85 MW electrolysis production plant for H_2 and O_2 for CO_2 capture and producing bio-proteins. ***Start of production in 2024.***
- NAUTILUS: At Becancour, 240 MW electrolysis production plant for green hydrogen production for fertilizers (urea/ammonia). ***Start of production is in 2025*** [**11**].

PLANETARY HYDROGEN [SURVEY COMPLETED]
205-260 SAINT RAYMOND BLVD.
GATINEAU, QC J9A 3G7

Planetary Hydrogen produced hydrogen using electrolysis powered by renewable energy. What makes their system different is the addition of alkaline rock to the electrolysis process. The result is a mineral hydroxide that when bond with CO_2 forms a bicarbonate that can be used as an "antacid" for the oceans. The process removes and stores 40kg of CO_2 from the air for every 1kg of hydrogen produced. In summary the Planetary Hydrogen electrolysis process produces green hydrogen, removes carbon from the atmosphere and produces a product that will de-acidify the oceans [**12**].

SIEMENS CANADA [SURVEY COMPLETED]
1577 NORTH SERVICE ROAD EAST
OAKVILLE, ON L6H OH6

Siemens produces the Silyzer 300 PEM electrolysis system to produce hydrogen in the MW range uses wind and solar as its base energy source. The Silyzer 300 can produce 100 to 2000 kg per hour with a plant efficiency of 75% [**13**]. Siemens has enlisted Ballard Power to develop a fuel cell power system for Siemens light rail division in Germany [**14**].

BIO-H2-GEN INC.
1687 HARTEN LANE
KINGSTON, ON K7L 4V1

Novel Electro-Chemical Process that utilizes water that has appropriate quantities of Hydrogen Sulphide H_2S and separates out H_2 and pure sulphur as products. The water source water for the process is farm wastewater, cities with wastewater treatment, and mining & industrial wastewater with mineral sulphates. The process is based on the sulphur cycle where in an anaerobic environment sulphate reducing bacteria produce H_2S and then on contact with air it is reduced to SO_2. In an aerobic environment SO_2 forms H_2SO_4 on contact with air and H_2O [**15**].

HYDROGENICS CANADA
220 ADMIRAL BOULEVARD
MISSISSAUGA, ON L5T 2N6

Hydrogenics is a primary manufacturer of complete hydrogen generation and hydrogen-fuelled energy systems. For hydrogen production Hydrogenics manufactures both Alkaline and PEM electrolysers that produce hydrogen for industrial uses, fuelling stations and for storage and transportation of energy in power-to-gas systems. For power generation Hydrogenics produces PEM fuel cells for transportation, backup power systems, free standing electrical power plants and UPS systems [**16**].

NEXT HYDROGEN
HEAD OFFICE — 102-2680 MATHESON BLVD. EAST
MISSISSAUGA, ON L4W 0A5

Next Hydrogen builds utility scale/WM size alkaline fuel cell electrolysers to produce hydrogen. Their electrolysers are designed to take advantage of intermittent energy sources like wind or less expensive off-peak grid electricity. The electrolysers have a "overdrive" capability which lets they operate at twice the capacity to reduce the number of units needed and hence more economical. The capabilities come from their redesign of the fuel cell flow ability. Each of their half cells can accommodate a variable flow of both liquid and gas. They have eliminated common flow manifolds to allow higher flow rates to and from the fuel cell. Therefore, the fuel cell has an "overdrive" capability to produce twice as much hydrogen than normal. They fuel cell are pre-built units that can be dropped into a customers' location without large infrastructure investments [**17**].

NU:IONIC TECHNOLOGIES (CANADA) INC.
67 MAIN STREET
FREDERICTON, N.B. E3A 1C2

Nu:ionic uses microwave technology to convert natural gas and renewable biogas to hydrogen in a small-scale gas reformer that is compact, more efficient, simpler in design and more economical.

Nu:ionic technology is an on-site, on-demand hydrogen production using natural gas in a steam methane reforming process to produce from 100kg to 15,000 kg per day of hydrogen.

The system uses onsite pipeline available natural gas and proven steam methane reforming (SMR) to reduce the cost and emissions with the use of low carbon electricity [**18**].

SOLARVEST BIOENERGY, INC.
3867 GREENFIELD ROAD
SUMMERVILLE, PE C0A 1R0

Proprietary hydrogen-producing algae strain. Capture carbon dioxide in photobioreactors, using Solarvest proprietary micro-algae to convert industrially produced CO_2, waste nutrient streams and solar energy into algal biomass by photosynthesis.

Solarvest has develop genetically engineered algal strains that cyclically produces hydrogen, under lab conditions. The Solarvest proprietary method has many improvements over the prior art in the industry that reduces cost of equipment and increases production capacity of algae. The prior art requires two photobioreactors to produce hydrogen. The first photobioreactor is used for the biomass to capture CO and the second for H_2 extraction. The Solarvest platform uses an innovative gene circuit engineered to inter-oscillate between CO_2 capture and H_2 production in a single photobioreactor reducing the capital cost of equipment by 50% and reduces the physical footprint. The second improvement over the prior art is that nutrient content of the environment for the algae. Current techniques require the restriction of macro-nutrients, such as sulphur, from the cultures to induce the production of hydrogen which stresses the algae and leads to a short production cycle. The Solarvest platform does not deprive the culture of necessary nutrients resulting in production cycles that last week's not days as in prior art. There is also ongoing research into reducing the CO_2 demand and replacing it with solar energy. At the end of the process metabolically modified organisms are being developed which will extract valuable proteins and or lipids to commercially use the resulting algal biomass as feedstock or future extract biomolecules. The commercialization of the by-product can make the whole process revenue positive [**19**]

1.8.2 Hydrogen Production Companies

ENBRIDGE GAS [SURVEY COMPLETED]
500 CONSUMERS RD.
NORTH YORK, ON M2J 1P8

Enbridge in partnership with Hydrogenics has built the Markham District Energy Facility that is the largest Power-To-Gas system in North America. The power to gas system takes excess electricity from the Ontario power grid and used to store energy through electrolysis that splits water into hydrogen and oxygen. The compressed hydrogen (fuel) is then stored on site and converted back to electricity for the grid via PEM (Polymer Electrolyte Membrane) Fuel Cell during peak demand or blended in small amounts into the natural gas pipeline to produce a lower carbon natural gas. [20]

HYDRO QUEBEC [SURVEY COMPLETED]
EDIFICE JEAN-LESAGE
75 BOULEVARD RENE-LEVESQUE OUEST
MONTREAL QC H2Z 1A4

Hydro Quebec due to its vast capacity of hydroelectric generation it has outlined five hydrogen applications where its capacity can be used to produce green hydrogen:

- Ammonia and methanol production
- Heating buildings
- Road and rail transportation
- Carbon-neutral synthetic hydrocarbon fuels
- Renewable natural gas [21]

AIRE LIQUIDE
1250 RENÉ-LÉVESQUE BLVD W.
MONTREAL, QC H3B 5E6

Aire Liquide's goal is to have at least 50% of its hydrogen for its applications come from reforming of biogas, electrolysis, and carbon capture of hydrogen produced from natural gas by 2020. [22]

Aire Liquide is developing bio-hydrogen that is produced from bio-methane that is derived from bio-gas that comes from anaerobic digestion of biomass or sanitary landfills. [22]

Aire Liquide is leading a project to use renewable wind energy to power a electrolysis process to produce hydrogen and will operate five hydrogen charging stations in Denmark serving 60 hydrogen powered cars. [22]

Aire Liquide will increase its hydrogen production by 50% in Becancour, Quebec by installing a 20 MW PEM electrolyser using hydrogenics technology. This will prevent the emissions of 27,000 tons of CO_2 per year. [23]

Aire Liquide has developed a CO_2 cold capture system that increases the hydrogen production by up to 20% and captures 60 to 90% of the CO_2. The cold carbon can then be purified and used in beverage carbonization, food preservation or freezing applications. [22]

AIR PRODUCTS LTD.
7475 NEWMAN BLVD,
LASALLE, QC H8N 1X3

Air Products supplies hydrogen via hydrogen pipeline, onsite generation or bulk deliveries. They have a onsite hydrogen generation system that can produce up to 1,000 Nm3/hr at 99.999% purity. The hydrogen gas generation options include hydrocarbon reforming, off-gas cleanup, and electrolysis systems [24]

PRAXAIR CANADA
1 CITY CENTRE DRIVE, SUITE 1200
MISSISSAUGA, ON L5B 1M2

Praxair supplies hydrogen in Cylinders & Liquid Containers, bulk shipments, pipeline or provide onsite hydrogen production. [25]

MESSER CANADA
5860 CHEDWORTH WAY
MISSISSAUGA, ON L5R 0A2

Messer offers supply of hydrogen through delivery of canisters or through supply of equipment for production of hydrogen on site. Messer offers electrolysis, steam reforming, and pressure swing absorption (PSA) units for purification. These systems are customized to the customers' needs. The electrolysis units range from 0.5 to 100 Nm^3/hr with a purity of 99.9%. [26]

1.8.3 Hydrogen Transportation

CHANGE ENERGY [SURVEY COMPLETED]
2140 WINSTON PARK DRIVE UNIT 203
OAKVILLE, ON L6H 5V5

Change Energy provides end-to-end solutions for compressed gas fuelling solutions. They have two principal areas that they focus on:

- Compressed gas infrastructure for the refuelling of vehicles.
- Engineering systems for bulk delivery of compressed natural gas (CNG) to industries that are not accessible via pipeline and remote communities [27]

Hydrogen projects:

- GH2 Station – DTE Energy Technologies (Detroit).
- Servicing distributed generation and vehicle fuelling assets.
- Hydra Energy (B.C.) H_2 - 2014 H_2 Refuelling Stations VR.
- Union Gas (Chatham, ON) H_2 - 2013 Technical and business feasibility analysis for Power to Gas/Wind Farms application IE.
- Queen's University (Kingston, ON) H_2 - 2013 Infrastructure Ontario – Fuel cell feasibility study: Hydrogen infrastructure component IE.
- Hydra Energy (B.C.) H_2 - 2013 Waste Hydrogen Recovery Process Design (peer review) other.
- Newfoundland and Labrador Hydro (Holyrood, NL) H_2 - 2011/2013 Hydrogen production plant other.
- Purolator (Toronto, ON), Canada H2 ◊ ◊ 2010 Refurbishment of fuelling station VR. [27]

INNOVATIVE HYDROGEN SOLUTIONS [SURVEY COMPLETED]
200 INDUSTRIAL PARKWAY SOUTH
AURORA, ON L4G 3V6

Innovative hydrogen solutions provide equipment to produce on demand hydrogen oxygen gas mixture to be directly injected into the air intake stream of diesel internal combustion engines. The device uses a source of distilled water to fuel an electrolyser to produce the hydrogen and oxygen gases. The equipment can be installed on diesel trucks and well as on diesel generator sets used in marine applications. [**28**]

REDROCK POWER SYSTEMS [SURVEY COMPLETED]
REDROCK POWER SYSTEMS INC
CHARLOTTETOWN, PE

Red Rock Power Systems mission is to develop and commercialize fuel cell solutions for the marine industry. They are currently working on a feasibility study to build a zero emissions ferry that will cross from St. Catharines to Toronto in about one hour. It is a 24 m 147 passenger vessel that will be powered by a 1.5 MW RR-4 fuel cell and travel at 34 knots. The RR-4 fuel cell stacks produce 750 kW of power designed for ferries and tugs. Red Rock works with Ballard Power. [**29**]

TOYOTA CANADA [SURVEY COMPLETED]
1 TOYOTA PLACE,
TORONTO, ON M1H 1H9

Toyota offers the hydrogen powered fuel cell Mirai in the British Columbia and Quebec markets. These are the only two markets with hydrogen fuelling stations. The Mirai has a 500 km range and can be charged in five minutes and promotes a -30°C starting temperature capability. [**30**]

CANADIAN TIRE
2180 YONGE STREET
TORONTO, ON M4P 2V8

Canadian Tire is one of Canada's largest retailers specializing in the hardware, household goods and automotive sectors and operates several specialty outlets. Canadian tire also has fuelling stations at many of its locations as well as service centres along the 401 in Ontario. They have also been pioneers in hydrogen with the use of hydrogen powered forklifts in their Brampton distribution centre. They have increased their use of hydrogen by installed on site hydrogen generation in their Bolton distribution centre to fuel their forklifts.

Canadian Tire sources their forklifts through Wajax Equipment, the exclusive dealer for Hyster® products across Canada, incorporating the PEM fuel cells manufactured by Massachusetts-based Nuvera Fuel Cells. [**31**]

For hydrogen production on site, Canadian Tire uses the NH-300 from Next Energy Corporation that can produce 650 kg of hydrogen per day. The hydrogen production and storage are onsite but separate from the distribution centre. The hydrogen is piped to the distribution centre where a refuelling station is available for the forklift operators to refuel similar to a petrol fuelling station.

DANA
1400 ADVANCE ROAD
OAKVILLE, ON L6L 6L6

Dana supplies components to hydrogen fuel cell engine like fuel cell stack bipolar plates and balance of plant and hydrogen reformer components. Dana technology creates product value through precision stamping, laser welding, composite molding, integrated seals, and in-line coating. Increased performance, reliability and lower cost are features of Dana's bipolar plates. Dana prioritizes lightweight, energy-efficient balance of plant products for thermal and water management subsystems as a key to advance fuel cell engines. [**32**]

HONDA CANADA
180 HONDA BLVD,
MARKHAM, ON L6C 0H9

Honda produces the Honda Clarity in a Plug-in electric vehicle as well as a fuel cell powered vehicle running on hydrogen. At this time only the plug-in electric vehicle is available in the Canadian market. [**33**]

HYUNDAI CANADA
75 FRONTENAC DR,
MARKHAM, ON L3R 6H2

Hyundai produces the Nexo fuel cell vehicle that is powered by hydrogen that has a 570 km range and can refuel in approximately 5 minutes. Currently the Nexo is listed at $73,000 Canadian and as coming soon. [**34**]

METROLINX
97 FRONT STREET WEST
TORONTO, ON, M5J 1E6

Metrolinx is electrifying its regional rail system away from diesels locomotives with a target date of 2025. They are considering electrification using traditional overhead wire system / catenary system and a hydrogen fuel cell (hydrail) powered system. Metrolinx has completed a feasibility study report that concludes a hydrogen fuel cell powered locomotive system of individually powered cars are technologically and financially viable. The study indicates several advantages of the hydrogen rail system (hydrail) over the conventional overhead wires catenary system. Some of the key advantages are:

- Catalyst for developing high skill level jobs in the hydrogen economy in Canada, specifically Ontario.
- Opportunity to leverage hydrogen production infrastructure to other transportation applications as well as other hydrogen sectors.
- No modification to the track system (i.e. lowering tracks, raising bridges, clearing trees, etc.).
- Potential to roll out the electrification ahead of the scheduled 2025 date due to ability to use existing track without modification.
- Potential to roll out electrification through entire system due to no modification of tracks.
- Hydrogen can be produced off peak times allowing for the purchase at optimum rates to reduce cost. [**35**]

1.8.4 Hydrogen Remote Power Systems

EVOLUGEN [SURVEY COMPLETED]
41 VICTORIA STREET
GATINEAU, QC J8X 2A1

Evolugen is the re-branding of Brookfield Renewable that is focusing on renewable energy systems for Canada. Evolugen builds owns and operates the renewable energy asset and sells the Renewable Energy Credits to customer to reach their renewable energy goals. They also will also work with clients on demand side energy management as well as onsite generation and storage. They generate approximately 5,800 GWh of energy per year from 33 hydroelectric facility and 3 wind farms. [**36**] They have generation stations in Ontario, Quebec and British Columbia.

TUGLIQ ENERGIE CO. [SURVEY COMPLETED]
2060 RUE DE LA MONTAGNE, SUITE 400, C.P. 401
MONTREAL, QC H3G 1Z7

Tugliq Energie is a renewable energy solution firm. They specialize in bringing renewable energy to remote locations that are typically reliant on the diesel generators for energy generations. Sites include remote northern communities and island communities. These sites also are some of the most affected by the negative ramifications of climate change. Tugliq uses a diverse set of renewable energy generation and storage technologies to accomplish a reliable renewable micro-grid solution.

These solutions can be new and stand alone or integrated into an existing diesel generator set to reduce the fuel consumption. Their most notable project from a hydrogen perspective is their Reglan 1 project. This project was installed in arctic conditions and includes a 3MW wind turbine for generation, with storage 1.5 kWh flywheel storage, 250 kWh Lithium-ion battery storage and a 4MWh hydrogen loop. The flywheel storage is for rapid fluctuations, the lithium batteries are for spinning reserves and backup while the hydrogen loop is for long term storage. The hydrogen loop consists of an electrolyser for hydrogen production, hydrogen storage and a fuel cell for re-electrification of hydrogen. [**5**]

WAJAX
229 UNIVERSITY AVE. UNIT B
BELLEVILLE, ON K8N 5S3

Wajax Equipment, the exclusive dealer for Hyster® products across Canada, incorporating the PEM fuel cells manufactured by Massachusetts-based Nuvera Fuel Cells. Wajax provides services like planning, technical support, installation, and training for the fuel cell systems. The hydrogen power systems are retrofitted into existing equipment removing risk of acid spills and other operational issues with battery powered forklifts. [**37**]

1.8.5 Hydrogen Process Use

ARCELORMITTAL DOFASCO [SURVEY COMPLETED]
330 BURLINGTON ST. E.
HAMILTON, ON L8N 3J5

ArcelorMittal Dofasco is a North American steel manufacturer working with automotive, energy, packaging, and construction companies to develop stronger, lighter and more sustainable products. The steel industry is a high emitter of CO_2 and hydrogen can be used in process to reduce emissions. [38]

CRH CANADA GROUP
2300 STEELES AVENUE WEST, 4TH FLOOR
CONCORD, ON L4K 5X6

CRH operates two cement plants and 14 terminals servicing the great lakes region in Canada and the northeast United States. They are part of the CRH America's Materials, a vertically integrated supplier of aggregates, asphalt, cement, ready mix concrete and paving material. [39]

1.8.6 Hydrogen Services and Balance of Systems

CANADIAN NUCLEAR LABORATORIES (CNL) – ONTARIO [SURVEY COMPLETED]
286 PLANT RD
CHALK RIVER, ON K0J 1J0

CNL in their chalk river facility is looking at expanding the hydrogen program looking to take a lead role in the demonstration of hydrogen for the bulk transportation sector. [40] CNL is researching into hydrogen production and storage of hydrogen. They are also doing research into hydrogen isotopes that are contained in heavy water for the cooling of nuclear reactors. [40]

EMCARA GAS [SURVEY COMPLETED]
67 WATSON RD. S.
GUELPH, ON N1L 1E3

Emcara Gas specialized in pressure relief valves for hydrogen fuelling and bulk hauling systems. [41]

GDH [SURVEY COMPLETED]
34 DURWARD PL.
WATERLOO, ON N2L 4E4

GDH is an engineering consulting firm whose work ranges from concept/pre-feasibility studies to overseeing construction. Their projects have included hydrogen production, storage and applications /end use. Hydrogen production has encompassed coal gasification, electrolysers (PEM and alkaline) steam reforming, and thermal devolution. Storage has included system using compression and liquification. Applications have included power-to-gas, power to ammonia, hydrogen mobility and industrial uses. [42]

HYDROGEN OPTIMIZED ONTARIO
1800 17TH STREET EAST
OWEN SOUND, ON N4K 1Z4

Hydrogen Optimized Ontario is a hydrogen technology company that designs, develops and builds large scale green hydrogen projects using innovative hydrogen technologies. Hydrogen Optimized Ontario is founded by the past president of Stuart Energy, Andrew Stuart. [43]

NIKKISO
530 McNICOLL AVENUE
TORONTO, ON M2H 2E1 [41]

Nikkiso Cryogenic Industries is a recognized leader focused on the design, fabrication and maintenance of compressed H_2 facilities. [44]

SIM COMPOSITES
357, RUE FRANQUET
QUÉBEC, QC G1P 4N7

Sim Composites produce a new generation of composite and nanocomposite ion exchange material called SiMION for application in fuel cells. Sim Composites also produces a non-carbon supported catalyst nanoparticles layer for fuel cells. If offers a large surface area with extreme low loading ratio of hydrogen concentration to area. [45]

Sim composites offers testing services for fuel cells and fuel cell stacks to universities and industry reducing their need to invest in capital equipment and training of staff in specialized processes. Sim composites also provides third party verification of fuel cell performance. [46]

XEBEC
730 BOULEVARD INDUSTRIEL,
BLAINVILLE, QC J7C 3V4

Xebec produces Pressure Swing Absorption (PSA) systems to purify off gases like hydrogen into a pure and ultra-pure form. Xebec's proprietary Xebec PSA Systems remove contaminants like water vapour, carbon dioxide, carbon monoxide, methane, nitrogen and other trace gases typically contained in steam reforming and other hydrogen-containing off gas streams.

PSA systems cycle faster than conventtional systems resulting in holding tanks that can be 5-15 times smaller therefore the system has a smaller footprint. [47]

Section 1: Hydrogen Business Survey Results
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SECTION 2

Investigating Hydrogen Energy-Oriented Research

by Universities of Ontario, Quebec and the Maritimes

Section 2: Investigating Hydrogen Energy-Oriented Research

TABLE OF CONTENTS

2 INVESTIGATING HYDROGEN ENERGY-ORIENTED RESEARCH

by Universities of Ontario, Quebec and the Maritimes

2.1 Introduction

Hydrogen can be stored, transported, and used as an energy carrier and recently gained potential as an alternative energy storage and distribution system which is known as hydrogen economy. This concept was first proposed at the beginning of the 1970s at General Motors (GM) Technical Centre by "John Bockris" in the Miami meeting on hydrogen. [1]

This report discusses briefly the most significant research on the hydrogen economy and hydrogen energy conducted in the universities of Ontario, Quebec, and Maritimes (Nova Scotia, New Brunswick, Newfoundland) from 2014 to 2020. This review focuses on research post-2014 as revised hydrogen regulations and standards were enacted after this year. [2,3,4,5,6]

Hydrogen-based energy systems in literature are frequently classified by production, storage, and utilization. Safety is another important aspect. [1,7,8,9,10,11,12,13] (FIGURE 2.1).

This report uses the classification of Hydrogen Production, Storage, and Utilization for grouping the hydrogen research. The purification of the hydrogen is grouped with hydrogen production. The studies showed that most publications, books, and articles focus on methods for hydrogen production and storage. Hydrogen production can be categorized into four main groups of electrolysis, photolysis, biolysis, and thermolysis. Secondary energy types include radiation, plasma, and biological energy as other sources for producing hydrogen. [1]

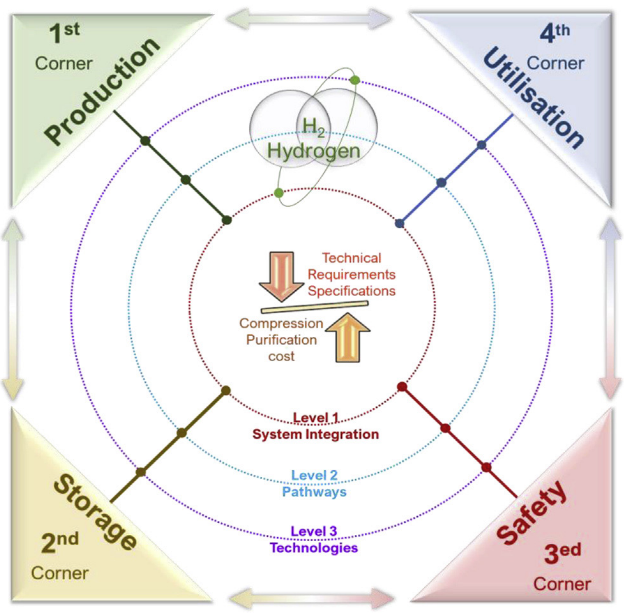

FIGURE 2.1 Hydrogen Square [1]

2.1.1 How to Use the Report

In the following report, short descriptions highlight research at different universities, listed by:

2.X Research topic (production, storage, utilization)
2.X.X. Province
University

With each university a brief explanation (or a part of the abstract) is provided from the article/patent related to different researchers of that university. For more information, a database is provided with the title of the papers, articles, and the related links and classification.

2.2 Hydrogen Production Research

2.2.1 Ontario

BROCK UNIVERSITY

DR. ART VAN DER EST studied the dihydrogen evolution in the PS I–NQ(CH2)15S–Pt nano construct from a biochemical point of view and the effect of different conditions in the rate of dihydrogen evolution [**14**].

CARLETON UNIVERSITY

DR. EDGAR MATIDA has developed a reaction mechanism to model the kinetics of hydrogen production from the decomposition of methane and has compared the pyrolysis of hydrocarbons from several combustion mechanisms to obtain the elementary reactions of this mechanism. The new mechanism reduces the error introduced from existing models for predicting the amount of hydrogen production up to 15%, depending on residence time and temperature levels. [**15**]

LAKEHEAD UNIVERSITY

DR. LIONEL CATALAN developed a noncatalytic kinetic model to provide thermodynamically consistent decomposition rates at methane conversions approaching equilibrium in an industrial-scale liquid metal bubble reactor (LMBRs). He asserted that a realistic reactor design must account for the coupling between reaction kinetics and hydrodynamic effects. [**16**]

Also, **DR. AICHENG CHEN** developed a high-yield and reproducible hydrothermal route to synthesize novel well-knit (i.e., solid and compacted) and porous anatase TiO_2 microspheres, consisting of morphologically controlled and uniform TiO_2 nanorods. These TiO_2 microspheres showed good performance in the generation of hydrogen. [**17**]

In another study, **DR. WU** concentrated on the recent advances in the synthesis of TiO2 microsphere-derived photocatalysts and their applications for efficient solar fuel H_2 evolution from water splitting and reviewed the advanced strategies for the fabrication of TiO_2 microsphere-based materials. [**18**]

McMASTER UNIVERSITY

DR. JAMES COTTON investigated the unique complementary roles of electrolysis and thermochemical decomposition of water to reduce the costs of hydrogen production. He asserted that thermochemical methods have a significantly higher thermal efficiency, but electrolysis can take advantage of low electricity prices during off-peak hours, as well as intermittent and de-centralized supplies like wind, solar or tidal power. [**19**]

Also, **DR. DREW HIGGINS** focuses on the design, synthesis, and characterization of novel nanomaterial catalysts, and their integration into electrochemical devices, such as fuel cells or electrolyzes. [**20**]

DR. YOUNGGY KIM studies the high purity H_2 production using microbial electrolysis cells (MECs) and the effect of methanogenesis. He found that a special condition (mentioned in the article) will allow high purity H_2 production, low energy consumption for O_2 production, and minimal O_2 exposure on bioanodes, enabling sustainable wastewater treatment and energy recovery using MECs. [**21**]

QUEEN'S UNIVERSITY

DR. BRANT PEPPLEY manufactured and tested 30-cell oxygen electrode supported planar solid oxide electrolyzer cell (SOEC) stack module at different operation conditions in steam electrolysis mode for hydrogen production and investigated the influences of operation conditions on the polarization loss of high-temperature water electrolysis. [**22**]

ROYAL MILITARY COLLEGE OF CANADA

DR. MAYUR MUNDHWA studied the parametric comparison between segmented and conventional continuous layer configurations of the coated combustion-catalyst to investigate their influence on the performance of methane steam reforming (MSR) for hydrogen production in a catalytic plate reactor (CPR). [**23**]

Also, **DR. CHRIS THURGOOD** investigated the use of Volatile Organic Compounds for Solid Oxide Fuel Cells (SOFCs). [**24**]

In another study, **DR. MUNDHWA** investigated the performance of a catalytic plate reactor coated with different patterns of distributed layers of reforming and combustion catalysts for the endothermic methane steam reforming (MSR) coupled with the exothermic methane combustion to produce hydrogen. [**25**]

TRENT UNIVERSITY

DR. IGOR SVISHCHEV studied the properties and applications of supercritical water in energy generation systems, such as the GEN IV super-critical water-cooled nuclear reactor and its use for hydrogen co-generation. [**26**]

UNIVERSITY OF GUELPH

DR. ANIMESH DUTTA studied the production of hydrogen from biomass by chemical looping thermal gasification of biomass and biomass conversion in supercritical water. [**27**]

Also, **DR. AICHENG CHEN** investigated the use of economically viable and advanced OER catalyst made of cobalt/graphene nanocomposite quantum dots (QDs) for solving the limitation of electrochemical water splitting for hydrogen production. [**28**]

UNIVERSITY OF OTTAWA

DR. JUAN SCAIANO evaluated the photocatalytic activities of the heterogeneous photocatalysts (based on electrospun fibers composed of polyvinylpyrrolidone and titanium propoxide) for the generation of H_2 upon UV (368 nm) or visible (630 nm) light excitation. [**29**]

In another study by **DR. ZISHENG ZHANG** a titanium metal carbides (Ti_3C_2) was combined with a photoactive material (BiOBr), and as-prepared composite exhibited excellent photocatalytic activities in both water detoxification and water splitting. [**30**]

DR. DARRIN RICHESON studied the electrocatalytic generation of H_2 from neutral water in acetonitrile using manganese polypyridyl complexes with ligand assistance. [**31**]

UNIVERSITY OF TORONTO

DR. HEATHER MACLEAN conducted a project on environmental and economic analysis on a life cycle basis of Canadian hydrogen sources for biofuel production. [**32**].

DR. FOREST WANG represented the model of a synergized photo-thermochemical hydrogen production and photovoltaics into a concentrated sunlight use. He asserted that such a simple integration of photo-thermochemical hydrogen and photovoltaics would create a pathway toward cascading use of sunlight energy. [**33**]

DR. MAAN AL-ZAREER proposed the conceptual integration of the generation IV nuclear reactor, the gas-cooled fast nuclear reactor, and the thermo-electrochemical copper-chlorine cycle, a Brayton cycle, and a Rankine cycle for hydrogen and electricity production. [**34**]

DR. SAMY GHOBRIAL studied the amorphous Ni-Nb-Y alloys for hydrogen evolution electrocatalysts and presented that the ball-milled Ni-based amorphous-based materials are promising catalysts for electrochemical hydrogen production. [**35**]

DR. EDWARD SARGENT demonstrated a new photocatalyst for hydrogen evolution based on metal epsilon-near-zero metamaterials. The resulting photocatalyst achieves a hydrogen production rate of 9.5 μmol h−1 cm−2 that exceeds, by a factor of 3.2, that of the best previously reported plasmonic-based photocatalysts for the dissociation of H_2 with 50 h stable operation. [**36**]

Also, **DR. GEOFFREY OZIN** investigated a new hydrogen-evolution heteronanostructured photocatalysts and studied the solar-powered photocatalytic hydrogen production properties of these heteronanostructures. [**37**]

UNIVERSITY OF WATERLOO

DR. JANUSZ KOZINSKI studied the gasification of agricultural crop residues such as soybean straw and flax straw in subcritical water (300 °C) and supercritical water (400 and 500 °C) for H_2 production. The findings suggest that supercritical water gasification could be an efficient green technology for H_2 production from waste biomass. [**38**]

DR. HYUNG-SOOL LEE studied the efficient hydrogen recovery method with CoP-NF as a cathode in microbial electrolysis cells. [**39**]

In another study, **DR. ERIC CROISET** investigated the effect of promoting a 15 wt.% Ni/Al2O3 catalyst with small amounts of Mo (0.1 and 0.5 wt.%) to produce H_2 via propane oxidative steam reforming. [**40**] Also, Dr. Croiset studied the glycerol reforming under supercritical water conditions (450–575 °C, 250 bar) for hydrogen production in an empty Inconel 625 reactor. [**41**]

DR. ROBERT VARIN reviewed complex hydride systems for hydrogen (H_2) generation for supplying fuel cells. Practical application aspects of hydride systems for H_2 generation/storage are also briefly discussed. [**42**]

DR. ASHRAF LOTFI did a Modelling and Experimental Study of Methane Catalytic Cracking as a Hydrogen Production Technology. [**43**]

In another study, **DR. MARYAM YOUNESSI SINAKI** did a numerical investigation on the number of active surface sites of carbon catalysts in the decomposition of methane. [**44**]

Also, **DR. TONG LEUNG** presented a p-type ZrO_2 nanoplate-decorated ZrO_2 nanowire photocathode with a high photoconversion efficiency that makes it potentially viable for commercial solar H_2 production. [**45**]

DR. JOHN WEN represented the kinetics and reaction processes of 40-nm and 1-μm aluminum powders with water to produce hydrogen at atmospheric pressure. [**46**]

DR. MICHAEL FOWLER investigated the synergistic roles of off-peak electrolysis and the thermochemical production of hydrogen from nuclear energy in Canada. [**47**]

UNIVERSITY OF WESTERN ONTARIO

DR. NIGEL BLAMEY did a project on pieces of evidence for seismogenic hydrogen gas, as a potential microbial energy source on Earth and Mars. [**48**]

Also, **DR. NOHA NASR** investigated different scenarios towards the optimization of fermentative H_2 production from synthetic and real wastes using pure and mixed cultures. [**49**]

DR. AJAY RAY tested a photocatalytic system for hydrogen production comprising ZnO as a photocatalyst, Eosin Y photo-sensitizer, triethanolamine electron donor, and platinum co-catalyst. [**50**]

DR. HUGO DE LASA investigated hydrogen production via water dissociation using Pt–TiO_2 photocatalysts. [**51**]

DR. LEI ZHANG studied a highly efficient and stable catalyst (facile one-step synthesis of tunable nanochain-like Fe–Mo–B) for oxygen evolution reaction. [**52**]

DR. HOSSEIN KAZEMIAN evaluated the thermodynamic parameters of the methano-SR reaction in hydrogen production using Ni-Mo-Cu/-alumina trimetallic catalysts. [**53**]

DR. ARGYRIOS MARGARITIS studied the use of the anaerobic photosynthetic bacterium Rhodopseudomonas sphaeroides for producing hydrogen from glucose. [**54**]

DR. SONIL NANDA used wheat straw as a candidate lignocellulosic biomass to produce hydrogen fuel through hydrothermal gasification. [**55**]

DR. KAMRAN SIDDIQUI studied the two-step ZnO/Zn thermochemical water splitting cycle for hydrogen production with a parametric study and defining reactor configuration. [56]

MS. BIANCA RUSINQUE studied the hydrogen production by photocatalytic water splitting under near-UV and visible light as her thesis and reported high efficiencies in terms of hydrogen production via water splitting using 2.0v/v% ethanol as a scavenger, platinum, and palladium as noble metals on TiO_2 photocatalysts at three metal loadings (1.0, 2.5 and 5.0wt%). [57]

DR. HUGO DE LASA investigated the photocatalytic hydrogen production using mesoporous TiO_2 doped with Pt. [58]

UNIVERSITY OF WINDSOR

DR. OFELIA JIANU investigated a quench cell configuration for the quenching of cuprous chloride (CuCl) for the thermochemical copper-chlorine cycle (Cu-Cl) to improve the efficiency of hydrogen production. [59] She proposed an experimental design to examine the dissolution of cuprous chloride in an aqueous hydrochloric acid solution in order to observe the reaction time and kinetics with application to hydrogen production. [60] In another study, she developed new correlations for the solubility of the CuCl-HCl-H_2O ternary system, which are essential to providing accurate boundary conditions for the transport processes in the copper-chlorine (Cu-Cl) cycle. [61] She experimentally studied the effect of anolyte concentration and electrical potential on electrolyzer performance in thermochemical hydrogen production using the Cu-Cl cycle. [62]

Dr. Jianu also experimentally studied the metastability of CuCl2 in H_2O-HCL for applications to the Cu-Cl thermochemical cycle to decrease crystallizing (precipitating) temperature and reduce the thermal energy requirements of the cycle. [63] In another study as a member of an international team of researchers from five countries – Canada, U.S., China, Slovenia and Romania – she presented the recent advances on the development and scale-up of the copper–chlorine (CuCl) cycle for thermochemical hydrogen production using nuclear or solar energy. [64] At the intelligent Fuels and Energy Laboratory(I-Fuels), Dr. Jianu is continuing research on the Cu-Cl cycle in different aspects of transport phenomena to identify irreversibilities within the cycle and improve its efficiency.

DR. JICHANG WANG developed a synergistic quaternary CdS-MoS2-WS2-Pt photocatalyst via a facile microwave-assisted method as a photocatalyst for efficient hydrogen evolution reaction. [65] In another study by Dr. Wang, he reported a facile transformation of copper substrates into CuxS coated electrodes for the improved electrochemical production of hydrogen. [66]

DR. JERALD LALMAN focused on synthesizing and employing one-dimensional (1D) titanium dioxide (TiO_2) for hydrogen (H_2) production. [67] In another study by Dr. Lalman, the biological H_2 production processes utilizing carbon-based agriculture feedstocks and water are examined. [68] Also, he examined continuous H_2 production using mixed anaerobic cultures fed glucose in upflow anaerobic sludge blanket reactors (UASBRs). [69]

MS. MINA AMINNEJAD investigated the bio-hydrogen and bio-methane production from potato waste in her thesis. [70]

WILFRID LAURIER UNIVERSITY

DR. RODERICK MELNIK studied the reaction mechanism of producing hydrogen via water splitting on the different surfaces of cubic silicon carbide (3C-SiC), the adsorption energy and the activation energy by using density functional theory. [71]

YORK UNIVERSITY

DR. HANY FARAG conducted a high profitability hydrogen production method based on electrolysis and chemical reaction. [72]

DR. SATINDER BRAR summarized mixed-culture system pretreatments such as heat, chemical (acid, alkali), microwave, ultrasound, aeration, and electric current, amongst others, and their combinations to improve the hydrogen production. [73]

DR. JANUSZ KOZINSKI worked on the subcritical and supercritical water gasification of lignocellulosic biomass impregnated with nickel nanocatalyst for hydrogen production. [74]

UNIVERSITY OF ONTARIO INSTITUTE OF TECHNOLOGY (ONTARIO TECH)

MR. HAI TANG developed a PSA-based framework for safety assessment and safety management of the nuclear-based hydrogen generation system to perform a risk-informed design for the Cu-Cl cycle. [75]

DR. IBRAHIM DINCER discussed opportunities and challenges for clean energy solutions from various dimensions, including social, economic, energetic, and environmental aspects. He compared different hydrogen production methods in this study. [76]

DR. MARC ROSEN presented an extended review of selected research and recent advances into hydrogen production from coal, biomass, and other solid fuels. [77]

In another study by **DR. HARIS ISHAQ**, a solar-wind hybrid trigeneration system is proposed and analyzed thermodynamically through energy and exergy approaches. The system consists of a solar heliostat field, a wind turbine, and a thermochemical copper-chlorine (Cu-Cl) cycle for hydrogen production linked with a hydrogen compression system. [78]

DR. KAMIEL GABRIEL presented preliminary results of an integrated hydrolysis reactor in the Cu-Cl hydrogen production cycle. [79]

DR. DINCER investigated various hydrogen production methods through thermochemical and hybrid cycles, including two steps (Zinc oxide), three steps (Sulphur-Iodine), four-step (Iron-Chlorine, Magnesium-Chlorine, and Copper-Chlorine) and hybrid types (Hybrid Sulphur). [80] In another study, he proposed and tested the ion exchange membranes in an electrolysis process for hydrogen production from acidic and alkaline solutions. [81] Also, he developed a novel photoelectrochemical reactor for the production of hydrogen and chlorine gas from spent hydrochloric acid generated in the galvanizing industry. [82] Dr. Dincer conducted another project in which three different renewable energy methods are considered with the wind, ocean thermal energy conversion (OTEC), and solar energy for clean hydrogen production, and Cu-Cl based thermochemical cycle is incorporated into systems to develop potential applications. [83]

In another study, Dr. Dincer proposed a nuclear-based integrated system for hydrogen production and liquefaction with a newly developed four-step magnesium–chlorine cycle. Furthermore, He presented a new three-step high temperature Cu-Cl thermochemical cycle for hydrogen production and evaluated its thermodynamic viability. [84]

MS. CANAN ACAR presented both experimental investigation and thermodynamic evaluation of a hybrid chloralkali-photoelectrochemical hydrogen production system. [85] Moreover, in another study, she investigated the economic, environmental, and social impacts of various hydrogen production methods, based on fossil fuel and renewable energy resources. [86]

DR. GREG NATERER presented recent Canadian advances in nuclear-based production of hydrogen by electrolysis and the thermochemical copper–chlorine (Cu–Cl) cycle. [87]

DR. HASAN OZCAN evaluated the cost assessment of nuclear hydrogen production methods using the Hydrogen Economy Evaluation Programme (HEEP) provided by the International Atomic Energy Agency. [88]

DR. ROSEN proposed a coal gasification-based integrated system to produce electrical power and hydrogen, where the hydrogen produced is stored in a chemical storage medium, which is ammonia. [89] He also, proposed a novel hydrogen production plant, including a thermochemical water decomposition cycle, a pressurized entrained flow gasifier, a water gas shift membrane reactor, a cryogenic air separation unit, a hydrogen-fuelled combined cycle for power production and a hydrogen compression system. [90] In another study by Dr. Rosen, he optimized an integrated coal gasification combined cycle system for the production of hydrogen in terms of energy and exergy efficiencies, and the amount and cost of the produced hydrogen and electricity. [91]

2.2.2 Quebec

UNIVERSITÉ DU QUÉBEC À TROIS-RIVIÈRES

MR. SAMUEL LEMAY performed first-principles calculations of the electronic structure of several catalysts and attempt to predict their efficiency for hydrogen evolution reactions in order to assist the design of photocatalytic systems for hydrogen production. [92]

MR. MERLY XAVIER investigated the fluidized bed reactor for the production of hydrogen from biomass by aqueous alkaline reforming. [93]

DR. PIERRE BENARD performed a study for hydrogen purification of a multi-component mixture (N_2/CO/CO_2/CH_4/H_2=0.007/0.012/0.17/ 0.021/0.79) by one-column VPSA with AC5-KS. [94]

MR. CAN TAO studied the biomass base-facilitated aqueous reforming for hydrogen production. [95]

MCGILL UNIVERSITY

DR. FAQRUL CHOWDHURY reviewed the basic principles and challenges associated with unassisted overall water splitting and highlights the recent technological advancements made on the device and system designs on the lab-scale. [96]

DR. JEFFREY BERGTHORSON compared the reactivity of industrial metal powders with water for hydrogen production in a batch reactor with sixteen different commercially-available industrial metal powders. [97] Also, he investigated the hydrogen production from the reaction of aluminum powder with liquid water for nano- and micron-sized spherical aluminum powders over the 20–200 °C temperature range. [98]

DR. ZETIAN MI studied the high-efficiency solar-to-hydrogen conversion on a monolithically integrated InGaN/GaN/Si adaptive tunnel junction photocathode. [99]

UNIVERSITÉ DE MONTREAL

DR. PATRICK HALLENBECK reviewed a variety of biological paths to hydrogen production and its Market deployment. He asserted that a variety of microorganisms are capable of producing hydrogen, and processes with mixed microbial consortia can make use of various agricultural, industrial, or municipal wastes. [100]

INSTITUT NATIONAL DE LA RECHERCHE SCIENTIFIQUE

DR. SATINDER BRAR studied biological hydrogen production using co-culture versus monoculture system from organic wastes. She asserted that the elaboration on coculture system has a huge potential for hydrogen production using complex organic wastes with viable applications towards industrialization. [101]

DR. FEDERICO ROSEI developed 1D/2D cobalt-based nanohybrid (CoNH) electrodes as electrocatalysts for hydrogen generation. [102]

UNIVERSITÉ DE SHERBROOKE

DR. JEAN-FRANÇOIS PÉLOQUIN presented a cost analysis including capital investments and operating costs, of hydrogen production by solar steam methane reforming. [103]

DR. JEAN-MICHEL LAVOIE reviewed the technologies for sustainable H_2 production, focusing on water electrolysis using renewable energy as well as on its remaining challenges for large scale production and integration with other technologies. [104]

UNIVERSITÉ LAVAL

DR. MARIA-CORNELIA ILIUTA studied the effects of carbon sphere (CS) and carbon nanotube (CNT) incorporation (as CT) in TiO2 composites and the roles of these CTs as a template, cocatalyst, and adsorbent in the photocatalytic hydrogen production. [105] Also, she proposed a reaction mechanism and a kinetic model to predict the rate of hydrogen production in the photocatalytic production of hydrogen in the liquid phase. [106]

DR. VINAYAK PACHAPUR summarized mixed-culture system pretreatments such as heat, chemical (acid, alkali), microwave, ultrasound, aeration, and electric current, amongst others, and their combinations to improve the hydrogen yields in the hydrogen production [107]

DR. TRONG-ON DO summarized the most recent studies on semiconductor composites for water splitting hydrogen production under visible light irradiation by sunlight-driven photocatalysts. [108]

2.2.3 New Brunswick

UNIVERSITY OF NEW BRUNSWICK, FREDERICTON

DR. MLADEN EIC studied the microwave-assisted dry reforming of methane over Ni and Ni–MgO catalysts supported on activated carbon (AC) with respect to reducing reaction energy consumption for hydrogen production. [**109**]

2.2.4 Nova Scotia

DALHOUSIE UNIVERSITY

DR. PETER ZHANG demonstrated that the synergetic effect of ultra-small ruthenium (Ru) clusters and intrinsic Brønsted acidity of zeolite frameworks can significantly promote the hydrogen generation of ammonia borane (AB) hydrolysis. [**110**]

DR. MITA DASOG studied the influence of hydrofluoric acid etching processes on the photocatalytic hydrogen evolution reaction using mesoporous silicon nanoparticles. [**111**]

2.2.5 Newfoundland

MEMORIAL UNIVERSITY OF NEWFOUNDLAND

DR. TOBIAS BRUECKNER enhanced the pyrolysis oils via distillation and pervaporation to improve its properties as fuel and produce value-added by-products. The separated by-product can be used for sustainable hydrogen production via electrolysis or the value-added chemicals can be used for other applications. [**112**]

DR. GREG NATERER developed a comprehensive predictive model for the CuCl/HCl(aq) electrolyzer stack in the electrochemical unit of the Cu–Cl cycle of hydrogen production. [**113**] Also, he presented a case study of a solar-based methanol plant that derives hydrogen and carbon dioxide material inputs from seawater on an offshore artificial island. [**114**] In another study, he discussed the recent advances in thermochemical hydrogen production with the copper–chlorine (Cu–Cl) cycle and presented a parametric study of multi-generation energy systems incorporating the Cu–Cl cycle with overall energy efficiency as high as 57% and exergy efficiency of hydrogen production up to 90%. [**115**]

2.3 Hydrogen Storage Research

2.3.1 Ontario

LAKEHEAD UNIVERSITY

DR. AICHENG CHEN discussed the recent advancement regarding palladium-based nanomaterials for hydrogen storage, as well as the effects of hydrogen spillover on various adsorbents including carbons, metal-organic frameworks, covalent organic frameworks, and other nanomaterials. [**116**] His other experimental study on the synthesis of palladium (Pd) nanoparticles and reduced graphene oxide (rGO) nanocomposites revealed that hydrogen storage capacity increased over 11 times in the β phase and more than five times in the β phase hydrogen sorption when compared to the Pd nanoparticles. [**117**]

McMASTER UNIVERSITY

DR. MOHSEN DANAIE examined the stability of the multi-layered thin-film structure Si (substrate)/Ta/Mg/Fe/Ta/Pd after deuterium absorption and desorption for hydrogen storage application. [**118**]

QUEEN'S UNIVERSITY

DR. BRENDAN MCCORMICK assessed the technical viability of battery and hydrogen energy storage systems, scaled for a Canadian residential dwelling with low annual electric power consumption. [**119**]

UNIVERSITY OF GUELPH

MR. EMMANUEL BOATENG developed a nanomaterial that demonstrated enhanced performance for the electrochemical storage of hydrogen with a discharge capacity of 88 mAh g-1, which was approximately three-fold higher than Pd-rGO electrode. [**120**]

UNIVERSITY OF TORONTO

DR. CHANDRA SINGH investigated the effect of topological defects and their possible use in a hydrogen storage system. This study suggests that graphene can be defect-engineered to develop effective hydrogen storage media. [**121**]

In another study by **DR. MAAN AL-ZAREER,** the efficient hydrogen compression and storage system are developed and analyzed thermodynamically through transient energy and exergy approaches. [**122**]

MR. SHWETANK YADAV studied the hydrogen storage through adsorption of metal decorated graphene, defective graphene, and metal decorated non-graphene 2-D carbon allotropes. [**123**]

DR. EUGENIA KUMACHEVA studied the developed a palladium nanoparticle for hydrogen storage and provided insight into the mechanism of catalysis of hydrogenation/dehydrogenation reactions by palladium nanoparticles with different shapes. [**124**]

DR. SINGH presented a comprehensive study of H_2 storage in alkali metal decorated and defect containing 2D borophene using density functional theory calculations. [**125**]

DR. JEREMY SCHOFIELD performed first-principles calculations to search high-capacity hydrogen storage media and studied Ca-decorated on perfect and defective C_3N nanotube. He showed that the Ca-decorated on defective nanotube can adsorb up to eight H_2 molecules with the average binding energy of 0.11 eV/H^2. [126]

UNIVERSITY OF WATERLOO

DR. ALI ELKAMEL quantified the hydrogen volumes upon utilizing Ontario, Canada's surplus electricity baseload, and explores the allocation of the hydrogen produced to four Power-to-Gas pathways in terms of economic and environmental benefits, focusing specific Power-to-Gas pathways. [127] Also, he proposed the optimal sizing of an electrolytic hydrogen production system using an existing natural gas infrastructure and surplus power in the Canadian province of Ontario. [128]

In another study, **DR. MICHAEL FOWLER** studied a stochastic programming approach for the planning and operation of power to gas energy hub with multiple energy recovery pathways. [129] Dr. Fowler investigated the effect and cost-efficiency of different renewable energy incentives and potential for hydrogen energy storage to the perceived viability of a microgrid project from the prospective of different stakeholders, i.e., government, energy hub operators and consumers in Ontario province, Canada. [130] He also applied an analytical hierarchy process to compare power-to-gas with other energy storage technologies in applications ranging from residential load shifting to bulk energy storage and utility-scale frequency support. [131]

DR. SHIRANI BIDABADI studied the nanostructured TM-Boron based hydrides for solid-state hydrogen storage (TM-transition metal). [132]

UNIVERSITY OF WESTERN ONTARIO:

DR. YANG SONG reviewed 22 types of representative potential hydrogen storage materials that belong to four major classes—simple hydride, complex hydride, chemical hydride, and hydrogen-containing materials. [133]

DR. YINING HUANG studied the storage of hydrogen by metal–organic frameworks using 2H solid-state NMR. [134]

DR. DIMITRE KARAMANEV reported the first in-depth cost analysis of a bio electrochemical technology for electrical power generation by bio generator which is a unique biological convertor of hydrogen to electricity. [135]

UNIVERSITY OF WINDSOR

DR. DAVID ANTONELLI invented four inventions in the field of hydrogen storage: 1) Metal hydrides and their use in hydrogen storage applications; 2) Synthesis and hydrogen storage properties of novel manganese hydrides; 3) Synthesis and hydrogen storage properties of novel metal hydrides, and; 4) Metal Hhydrazide materials. [136-139]

YORK UNIVERSITY

DR. HANY FARAG studied the hydrogen storage optimal scheduling for fuel supply and capacity-based demand response programs under dynamic hydrogen pricing. [140]

RYERSON UNIVERSITY

DR. KAAMRAN RAAHEMIFAR analyzed the advantages of energy incentives for all the stakeholders (the government, the energy hub operator, and the energy consumer) in an energy system. He showed that shows that battery storage and hydrogen storage are complementary technologies for reducing GHG emissions in Ontario. [141]

LAURENTIAN UNIVERSITY

DR. ZHIBIN YE demonstrated the first use of a family of cross-linked polymers synthesized from acetylenic monomers (diethynylbenzene and phenylacetylene) as new polymer precursors for the high-yield synthesis of nanoporous activated carbons of tuneable textural properties for supercapacitors, hydrogen storage, and CO_2 capture. [142]

UNIVERSITY OF ONTARIO INSTITUTE OF TECHNOLOGY (ONTARIO TECH)

DR. MARC ROSEN reviewed energy storage technologies, including storage types, categorizations, and comparisons. [143]

DR. CALIN ZAMFIRESCU proposed a modification to the Claude liquefaction process of hydrogen for increased efficiency in the storage of hydrogen. [144]

2.3.2 Quebec

UNIVERSITÉ DU QUÉBEC À TROIS-RIVIÈRES

MR. PENG LYU studied the effects of mechanical deformation on hydrogen storage properties of tife-based alloys. [145]

DR. JACQUES HUOT investigated the TiFe alloys for the purpose of improving the first hydrogenation by adding yttrium. [146] Also, he studied the effect of adding Zr on microstructure and hydrogen storage properties of BCC Ti1V0.9Cr1.1 synthesized by arc melting. [147] In another study by Dr. Huot, he studied the Mg-based compounds for hydrogen and energy storage. [148] He also studied the effect of adding hafnium to TiFe in order to enhance the first hydrogenation process. [149]

DR. RICHARD CHAHINE investigated the hydrogen storage in a two-liter adsorbent prototype tank for fuel cell-driven vehicles. [150]

DR. RENJU ZACHARIA reviewed solid-state hydrogen storage methods adopting different kinds of novel materials) metallic and intermetallic hydrides, complex chemical hydride, nanostructured carbon materials, etc.). [151]

DR. ALEXANDRE ASSELLI investigated the synthesis, microstructure, and hydrogen storage properties of Mg-based nanocomposites containing different concentrations of TiCrV and TiCr1.2V0.8 alloys. [152]

DR. HUOT reported the effect of macro and microstructure on the hydrogen storage properties of magnesium-based materials processed by cold rolling. [153] Also, he performed two synthesis methods to dope 52Ti–12V–36Cr alloy with Zr {sub 7} Ni {sub 10} and investigated the crystal structure and hydrogen storage properties of that. [154]

DR. ZACHARIA presented a detailed investigation of how the activation processes using KOH, CO_2, K_2CO_3, and H_3PO_4 modify the microstructure of olive stones-derived ACs and how they affect the ACs' hydrogen storage behavior. [155] In another study, Dr. Zacharia discussed the current status of the field and future challenge, ranging from important open fundamental questions, such as the density and volume of the adsorbed phase and its relationship to overall storage capacity, to the development of new functional materials and complete storage system design. [156]

DR. JINSHENG XIAO developed lumped parameter models for hydrogen storage and purification systems based on MATLAB/Simulink. [157] Dr. Xiao also numerically investigated the effect of flow-through cooling heat removal on the storage and thermal performances of a 20 m3 MOF-5 cryo-adsorptive bulk hydrogen reservoir. [158]

DR. ZACHARIA compared the isosteric heats of hydrogen absorption on microporous materials measured by isosteric and calorimetric–volumetric methods. [159]

DR. HUOT reported the microstructure and hydrogen storage properties of Ti0.95FeZr0.05, TiFe0.95Zr0.05, and TiFeZr0.05 alloys prepared by arc melting. [160]

UNIVERSITÉ DU QUÉBEC À MONTRÉAL

DR. ABDELKRIM AZZOUZ studied the hydrogen storage on adsorbents with high surface-to-bulk ratio – Prospects for Si-containing matrices. [161] Also, he developed an unprecedented strategy for achieving high dispersion of copper (0) or palladium (0) on montmorillonite-supported diethanolamine or thioglycerol which is a novel metal–inorganic–organic matrices (MIOM) that readily capture hydrogen at ambient conditions, with an easy release under air stream. [162] In another study, he synthesized metal-organic-clays (MOC) via insitu formation of Cu(0) or Pd(0) nanoparticles in montmorillonite-supported dendritic polyols for hydrogen storage. [163]

MCGILL UNIVERSITY

DR. ZETIAN MI developed a reversible hydrogen storage system based on low-cost liquid organic cyclic hydrocarbons at room temperature and atmospheric pressure. [164] He also submits the patent of this method. [165]

DR. ROBIN ROGERS reported an experimental and theoretical investigation of the structure of [B9H14]– and the energetics of some of its reactions implications for energy storage. [166]

CONCORDIA UNIVERSITY

DR. MAMOUN MEDRAJ proposed a thermodynamic database, constructed using the CALPHAD technique, for a thermodynamic study on the Mg–Al–Li–Na–H system for hydrogen storage properties. [167] Also, he performed thermodynamic modeling of the Al–Mg–Na–H system to understand the phase relationships and reaction mechanisms of the hydrogen storage process. [168]

2.3.3 New Brunswick

UNIVERSITY OF NEW BRUNSWICK, FREDERICTON

MR. JAMES TITAH explored the solid-state structures of LiH, NaH, KH, $LiAlH_4$, $NaAlH_4$, and Li_3AlH_6 in detail as potential hydrogen-storage materials using computational electron density methods. [169]

2.4 Hydrogen Utilization Research

2.4.1 Ontario

QUEEN'S UNIVERSITY

DR. BRANT PEPPLEY generated an in Honeywell's UniSim Design Suite to simulate the performance of a diesel fed steam reformer and a solid oxide fuel cell system for a Canadian remote community. He showed that replacing diesel generators with the proposed steam reformer and solid oxide fuel cell system would result in annual net efficiency improvements of 32%. [170]

UNIVERSITY OF TORONTO

MR. MATTHEW CHEN presented a power-to-gas model utilizing excess renewable energy that can support boating activities in Ontario. He designed the refuelling infrastructure, the fHuel+™ refuelling station, and the onboard hydrogen utilization system for a high-speed luxury boat, the Hydronautic+™. [171].

In another study by **DR. AIMY BAZYLAK** with the Nissan Research Center, they investigated the performance characteristics of a PEM fuel cell in dead-ended anode mode with both a pristine membrane electrode assembly (MEA) and a corroded MEA. [172]

UNIVERSITY OF WATERLOO

DR. HYUNG-SOOL LEE studied the syntrophic interactions between H_2-scavenging and anode-respiring bacteria that can improve current density in microbial electrochemical cells. [173]

MR. SUAAD AL-ZAKWANI studied the allocation of hydrogen produced via power-to-gas technology to various power-to-gas pathways in his thesis. [174]

In another study, **MR. EMMANUEL OGBE** represented integrated design and operation optimization of hydrogen commingled with natural gas in pipeline networks in his thesis. [175] In another thesis project,

MR. MEHRAN AKHOUNDZADEH presented a hydrogen hybrid powertrain for the union-Pearson railway. [176]

MR. MUNUR HERDEM developed a multiphysics modeling of a microchannel methanol steam reformer for high-temperature polymer electrolyte membrane fuel cell systems. [177]

In another comprehensive study, **DR. MICHAEL FOWLER** analyzed the hydrogen economy for hydrogen fuel cell vehicles in Ontario. [178] Also, he developed a generic mathematical model for the optimal energy management of future communities where hydrogen is used as an energy vector. [179]

UNIVERSITY OF WINDSOR

MR. MUDIT NIJHAWAN investigated the sustainable energy alternatives for providing enough power for the remote communities in northern Ontario. The primary energy sources that were studied in this study are solar, wind, and hydrogen. Results showed that hydrogen fuel cells are better alternatives for powering the communities. [**180**]

RYERSON UNIVERSITY

DR. CARLOS SABILLON introduced new techno-economic models for the optimal inclusion of Hydrogen Trains in Electricity Markets. [**181**]

UNIVERSITY OF ONTARIO INSTITUTE OF TECHNOLOGY

DR. HOSSAM GABER compared natural gas and hydrogen fuels for the purpose of energy conservation for a wide range of buildings via alternative energy generation methodologies. [**182**]

DR. MARC ROSEN described the role of hydrogen as an energy carrier and hydrogen energy systems' technologies and their economics. Also, he investigated energy benefits and the methods of achieving net-zero energy status for a solar building and reduction of greenhouse gas emissions through the integration of wastes streams (hydrogen) and transportation energy. [**183**]

2.4.2 Quebec

UNIVERSITÉ DU QUÉBEC À TROIS-RIVIÈRES

DR. RICHARD CHAHINE proposed a practical selecting procedure of adding hydrogen refuelling service to existing natural gas (NG) stations and related feasibility and future planning in Wuhan, China. [**184**]

DR. JINSHENG XIAO investigated the estimation of filling time for compressed hydrogen refuelling. [**185**]

DR. ALVARO MACÍAS FERNANDEZ compared the use of passive and active couplings in three-wheel fuel cell hybrid electric vehicles to reveal their strengths and weaknesses. [**186**]

DR. SOUSSO KELOUWANI addressed the design of systemic management to improve the energetic efficiency of an open cathode proton exchange membrane fuel cell (PEMFC) in a hybrid system. [**187**]

DR. LOIC XIAO developed a lumped parameter model that has been developed and a thermodynamical analysis for determining the final hydrogen mass for refuelling. [**188**]

DR. LOIC BOULON studied the influence of battery degradation over the performance of a fuel cell hybrid electric vehicle (FCHEV). [**189**]

DR. CHAHINE estimated the final hydrogen temperature of the fast filling of hydrogen storage tank under final pressures of 35 MPa and 70 MPa. [**190**]

MS. NASSIM NOURA presented an accurate energy management strategy (ems) for a fuel cell hybrid electric vehicle (FC-HEV). [**191**]

DR. KELOUWANI presented an experimental study on a bi-fuel generator (hydrogen-gasoline), the influence of mixture richness (for hydrogen). [192]

DR. ARASH SOLTANI investigated the principle of employing a modular energy system and how this principle is affecting the vehicular applications. [193]

DR. BOULON studied the trends in development and future perspectives of autonomous off-road farm vehicles premised on green energies, with on-site energy production as a byproduct. [194]

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE (ETS)

MR. MOHAMED-HAMZA LARAKI studied energy management in residential systems connected to autonomous networks in northern Quebec. New solutions have been studied and proposed which consist of integrating renewable energy sources (wind, solar, etc.) with diesel generators which would have a positive impact on the cost of electricity production as well as the rate of emission of greenhouse gases. [195]

MCGILL UNIVERSITY

DR. AGUS SASMITO evaluated the performance of a PEM fuel cell stack with variable inlet flows for vehicle application subjected to New European Driving Cycle (NEDC) by utilizing computational fluid dynamics (CFD) approach. [196] Also, he reviewed the advances in proton exchange membrane fuel cell with dead-end anode operation. [197] In another case of research, he studied the optimization of the membrane electrode assembly of a PEM fuel cell by response surface method. [198]

INSTITUT NATIONAL DE LA RECHERCHE SCIENTIFIQUE

DR. SHUHUI SUN systematically investigated the stability behaviors of the state-of-the-art Fe/N/C and Pt/C catalysts (as well as the activation time of the latter), under different cathode catalyst loadings, in the membrane electrode assemblies (MEA) in PEM fuel cells. [199]

UNIVERSITÉ DE SHERBROOKE

MR. JULES VOISIN presented a new approach to studying the impact of the climate on the optimal sizing of a stand-alone PV/hydrogen/battery-based hybrid building. [200]

CONCORDIA UNIVERSITY

DR. AKSHAY RATHORE reviewed Electric Vehicle Charging Station Location and focused on the most significant parameters considered in charging station location planning by various researches, its relevance, and pitfalls. [201]

2.4.3 Newfoundland

MEMORIAL UNIVERSITY OF NEWFOUNDLAND

MR. VENKATARAGHAVAN KUMARASWAMY developed a complete user-friendly Simulink model of the PEM fuel cell to implement the maximum power point tracking (MPPT) technique and maximum efficiency point tracking (MEPT) technique. [**202**]

DR. MOHAMED ALBARGHOT designed an integrated fuel cell to be added into the MUN Explorer AUV along with a battery bank system to increase its power system. [**203**]

MR. AMIN ETMINAN numerically simulated the performance of a Proton Exchange Membrane (PEM) fuel cell for two channels with rectangular and triangular cross-section areas. He reported that the temperature of the input gas remarkably enhances the output voltage of the PEM. [**204**]

Section 2: Investigating Hydrogen Energy-Oriented Research

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SECTION 3

TRANSPORTATION

A Review of Hydrogen as a Transportation Fuel

EASTERN CANADA

Section 3: A Review of Hydrogen as a Transportation Fuel

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SECTION 3 — FIGURES AND TABLES

3 A REVIEW OF HYDROGEN AS A TRANSPORTATION FUEL

EASTERN CANADA

3.1 Background

This section focuses on the application of hydrogen for heavy duty transportation and associated regulatory considerations.

3.2 Introduction

It is generally accepted, through the literature, that the very nature of the changing landscape in the movement of freight is driving changes in the need of specific products and services to support the North American trucking industry.

The existing Ontario-Quebec highway corridor is currently and expected to remain a major economic driver in support of the regional economy and providing an incredibly significant contribution in the overall movement of freight.

In general, a study of truck traffic today and projected future growth (all based on information prior to COVID-19) based on primary and secondary corridors, border crossings, way points, goods carried, and operating factors, it is evident that heavy-duty truck fleet operations in Ontario and Quebec are now mostly based on a hub-and-spoke model which reflects regional operations rather than cross-country.

It is also important to generally appreciate the scope and overall characteristics of the current diesel operated heavy-duty truck fleet including the number of vehicles, carriers, type, and age of the equipment operated and the impact of future regulations. In conjunction, it remains important to realize the nature, types and potential growth of available natural gas heavy-duty trucks and full electric heavy-duty trucks (currently in development and not commercially available) that can meet the requirements of certain segments of long-haul fleet operations along the Ontario-Quebec freight corridor.

The intent of this section is to capture and briefly present aspects of regional haul heavy truck traffic along the primary Ontario-Quebec freight corridors and to provide some insights relative to the design and selection of future hydrogen (H_2) powered heavy duty vehicles and hydrogen (H_2) station locations along this freight corridor to support the existing heavy-duty trucking industry.

Specifically, this section provides results of research and information provided in summary form to include the following key aspects:

- Summary of key Ontario freight corridors (overview – current – future growth)
- Summary of northeast U.S. freight corridors (overview – current – future growth)
- Ontario commercial traffic volume – macro view - 400 series of highways (including the QEW)
- Ontario commercial traffic volume – micro view - specific target sites – along 400 series highways
- Nature of truck traffic – Class 7 and Class 8, nature of traffic flow, nature of freight carried
- Current CNG refuelling stations – Ontario, Quebec and northeast U.S.

Note that this information is all based on a view of markets, freight trends and technology based on a perspective that is not influenced by the impact of COVID-19. It is highly likely the assumptions of market needs, freight trends, transportation platforms and corridors (across Canada and travel to/from the United States) will be impacted.

In summary, the objective of this section is to help determine the potential location(s) of hydrogen refuelling along the Kings-Highways (400 series and QEW highways) in Ontario based on future OEM hydrogen-fuelled heavy-duty trucks currently being demonstrated in the United States market.

As well, this section begins to address primary aspects of impacted codes, standards and regulations as they apply to over the road heavy duty hydrogen-fuelled vehicles and supporting refuelling equipment.

3.3 Overall Canadian Heavy-Duty Class 8 – 15 Tonne Truck Fleet

3.3.1 Terminology

The terminology used to identify **trucks, tractors, trailers** and **semis** are often used interchangeably, and often incorrectly. For the purposes of this report, the term **truck** will often be used to describe heavy-duty vehicles, both straight truck and tractor-trailer combinations, as many of the references cited utilize common, not technical terms. The full description and definitions of these terms may be found in **APPENDIX A3**.

The trucking industry has developed a set of its own language to define various aspects of the industry which may result in different interpretations by many trying to better understand its nature and operation. One example is the various definitions to define length of travel, **"long haul", "short haul", "regional haul" and "line-haul"**, which may be used in a general sense. For our purposes, "**long haul**" is defined as traveling more than 200 or 300 km and away from the driver's home terminal. Drivers are often gone from their home terminal for days or weeks at a time. The term "**regional haul**" will be used to describe trucks that travel more than 160 km which may or may not return to base the same day. "**Line-haul**" is described as moving freight from major cities or ports that are at least 1,500 km apart.

The definitions and understanding of these terms also change based on jurisdictions and various regulations. Further explanation may be found in **APPENDIX A3**.

The trucking trend for many years has been a move away from the traditional cross country "long haul" distances to shorter runs typically called "regional" or "corridor runs." The literature and trade magazines offer many examples and insights that have defined these macro trends and will not be addressed in any detail.

The intent of this report is to capture and briefly define aspects of truck traffic along the primary Ontario freight corridors, as the very nature of the changing landscape is driving changes in the product needs to support the industry and to guide selection of future hydrogen vehicles and hydrogen station locations.

3.3.2 Describing the Fleet

The overall Canadian Heavy-Duty Class 8—15 Tonne (15,000 kg) truck fleet can be described based on data published in the Canadian Vehicle Survey Report by Natural Resources Canada and Statistics Canada last published in 2009. [**1**], [**2**]

- Number and age of vehicles, geographic distribution
- Average distance travelled by heavy trucks by jurisdiction
- Diesel consumption rate of heavy trucks by jurisdiction
- Distance travelled by heavy trucks by configuration
- Distance travelled by heavy trucks by trip purpose
- Distance travelled by heavy trucks by activity type
- Distribution of heavy trucks by vehicle age
- Average distance travelled by heavy trucks by vehicle age, 2009
- Trip type – with province, between province, across Canada and U.S. border, outside Canada, 2009

This data was not reviewed to extract Ontario specific information but could be further used to aid in addressing future refuelling station locations.

There is also considerable information in the literature, not addressed in this section, that describes the Canadian Class 8 market as it relates to sales and registration data across Canada, by province and by OEM Brand.

Canadian Carriers - Fleet Tractor Population and HD Engine Market

There are approximately 183,000 trucks, tractors and trailers based on the "Top 100 Carriers for 2016" in Canada, in a recent published survey by Todays Trucking. [**3**]

The Top 10 and Top 100 Canadian carriers have approximately 20,500 and 42,500 tractors (Class 8 trucks) respectively as part of their rolling stock. **FIGURE 3.1** shows the number of tractors for the top 10, 20, 30, 40, 50 and 100 fleets. No carriers in the Top 100 have less than 50 tractors.

This generally illustrates there are many more carriers, fleet owners, owner operators and for hire trucking firms across Canada.

A detailed assessment of the top carriers based on primary company location (headquarters) might provide an indication of which carriers are operating in Ontario and Quebec. As a simple example, within the top 20 carriers

50% are headquartered in Ontario and Quebec. For the entire top 100 carriers 72% are headquartered in Ontario and Quebec. Specifically, 45 carriers are based in Ontario and 27 carriers are in the province of Quebec.

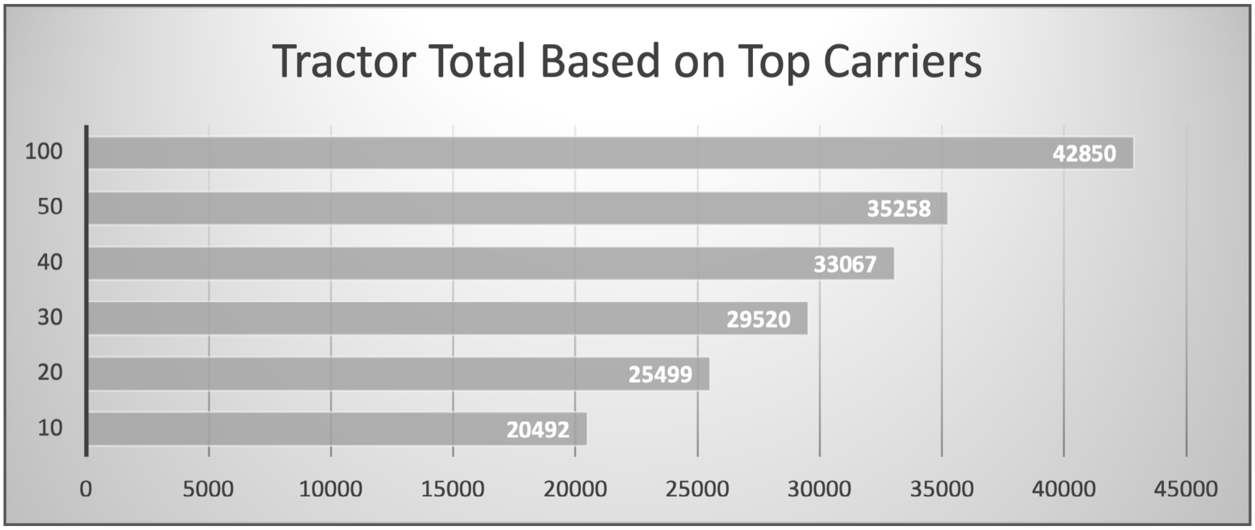


FIGURE 3.1 Tractor Total Based on Top Carriers

3.4 Canadian Trucking Industry Structure, Major Truck Freight Routes

This section is an overview of the structure of the trucking industry in Canada and identifies the major truck freight routes. This information is critical in understanding the primary traffic centres, routes for the consideration of hydrogen refuelling.

3.4.1 Canadian Trucking Industry Structure

"As of December 2014, there were 62,805 businesses whose primary activity was trucking transportation. Trucking includes many small for-hire carriers and owner-operators, and some medium and large for-hire companies that operate fleets of trucks and offer logistic services. Trucking companies were concentrated in four provinces: Ontario (41.6%), Quebec (15.5%), Alberta (15.5%), and B.C. (14.2%t).

The trucking industry can be divided into three main types of trucking activities.

1) FOR-HIRE TRUCKING SERVICES, which fall into two main categories:

- Less-than truckload (LTL); and
- Truckload (TL).

For-hire carriers can be further grouped as:

- Intra-provincial (i.e., operating exclusively within a provincial jurisdiction); and
- Extra-provincial (i.e., beyond provincial and national boundaries).

2) COURIER OPERATORS, who specialize in transporting parcels. As of December 2014, there were 11,815 companies with courier services as their main line of business.

3) PRIVATE CARRIERS, where businesses maintain a fleet of trucks and trailers to carry their own goods. These carriers' activities are not tracked, as they are part of companies whose main line of activity is not trucking (e.g. Walmart, Costco).

"In 2013 (the latest year for which data are available), more than 23 million road motor vehicles were registered in Canada. Medium and heavy trucks weighing 4,500 kilograms or more represented 4.3%." Note: this equates to approximately 989,000 medium and heavy-duty trucks.

Freight Traffic

In 2013 (the latest year for which data are available), for-hire trucking traffic amounted to 251.4 billion tonne-kilometres. Around 43% of that traffic involved an international movement.

In 2014, around 10.7 million two-way trucking movements were recorded at Canada/U.S. border points. Over 66% of these movements were related to Canadian registered trucks.

The same commodities dominated both exports and imports: automotive products, machinery and electrical equipment, other manufactured products, and agricultural products." [4]

3.4.2 Primary Across-Canada, within Provinces, Regional Haul Traffic Routes

FIGURE 3.2 "offers a glimpse of the freight transportation flows through Canada's transportation system. It shows Central Canada as an important hub for channeling freight movements. For instance, trucking activity is heavily concentrated along the Quebec-Windsor corridor to move foodstuffs, manufactured and other processed goods. This corridor also represents a key lane for rail trade with the U.S. Corridors of significant railway freight volumes are those transporting bulk commodities like grain, coal, and potash from the Prairie Provinces to ports on the west coast. On the return trip eastward, they transport import containers from B.C. ports to Southern Ontario and the U.S." [5]

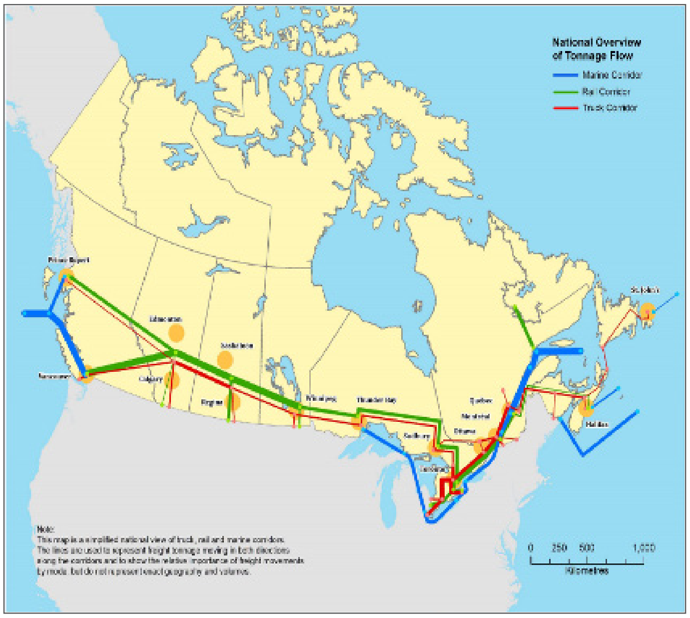


FIGURE 3.2 Canadian Freight Transportation Corridors

Additional detail surrounding Canadian rail yards, airports and marine ports as it relates to the movement of freight and the connectivity with road transportation of freight system can be found in the same reference but is not part of this study.

In summary, this report will focus only on the Ontario - Quebec corridor as the primary regional haul traffic corridor.

3.4.3 U.S. Border Crossings – Primarily North-South Traffic

Based on 2010 facts published by the Canada-U.S. Transportation Border Working Group (TBWG), the length of this common land and water border is 8,891 km and consists of 120 vehicular land ports of entry. Road crossings consists of 24 bridges and 1 tunnel with 28,814 trucks crossing the border each day. [6]

Based on the U.S. Department of Transportation's Freight Management and Operations Freight Facts, in 2012, 5.6 million trucks and nearly 4.1 million loaded containers entered from Canada into the U.S. [7]

Additional U.S. freight data and detail is available for a more extensive analysis but is judged to beyond scope of this report.

3.5 Primary Truck Freight Corridor: Ontario-Quebec Continental Gateway

3.5.1 Introduction and the King's Highways

In order to best begin to establish target locations for potential future hydrogen HD truck refuelling stations along the major Ontario-Quebec freight corridor one needs to basically understand the current highway infrastructure and related factors or influences.

This section provides a brief overview of the King's Highways, Ontario's freight supportive guidelines and major service and weigh scale centres.

Major focus of this section is on general freight movement and analysis along the major Ontario freight corridors leveraging information available through the Ministry of Transportation in Ontario and through targeted publications published by the McMaster Institute of Transportation and Logistics

The following sections provide some insight to the nature of truck traffic (route volumes, direction, etc.) along the Ontario – Quebec freight corridors.

In Ontario, this represents the "King's Highways" that is generally described to include the "400 series" of highways and includes the QEW (Queen Elizabeth Way). Primary focus of this report will be highway 401 (817 km from Windsor to the Quebec border) and the QEW highway (138 km from Toronto to Fort Erie).

FIGURE 3.3 High Level List of King's Highways

FIGURE 3.4 King's Highway - 401

FIGURE 3.3,[2] **FIGURE 3.4**[3] and **FIGURE 3.5**[4] provide a quick reference of the highways included and the basic geographic route of the 401 and QEW. [8]

Highway 401, in existence since 1952, primarily serves the counties of Essex, Kent, Elgin, Middlesex, Oxford, Waterloo, Wellington, Halton, Peel, Durham, Northumberland, Hastings, Lennox and Addington, Frontenac, Leeds and Grenville, & Stormont, Dundas and Glengarry. The primary towns include Windsor, Chatham, London, Woodstock, Kitchener-Waterloo, Cambridge, Guelph, Milton, Mississauga, Toronto, Pickering, Ajax, Oshawa, Bowmanville, Newcastle, Port Hope, Cobourg, Trenton, Belleville, Napanee, Kingston, Gananoque, Brockville, Morrisburg & Cornwall. [9]

The QEW, in existence since 1939, primarily serves the counties of Niagara, Hamilton (Wentworth), Halton & Peel which includes the towns of Fort Erie, Niagara Falls, St. Catharines, Grimsby, Hamilton, Burlington, Oakville, Mississauga & Toronto. [10]

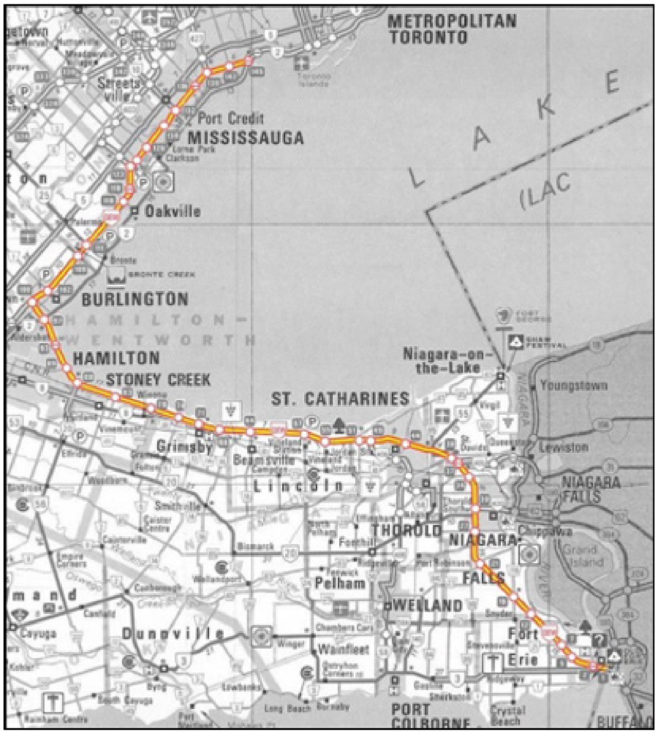


FIGURE 3.5 King's Highways — QEW

2 http://www.thekingshighway.ca/MILEAGE/400-series.htm (Accessed, 26 April 2021).

3 http://www.thekingshighway.ca/MAPS/Hwy401map.htm (Accessed, 26 April 2021).

4 http://www.thekingshighway.ca/MAPS/QEWmap.htm (Accessed, 26 April 2021).

3.5.2 Ontario's Transportation Priorities

During the Transportation Border Working Group Fall Plenary Toronto meeting in October of 2015, Ministry of Transportation Alison Drummond from the MTO presented on Ontario's transportation priorities, starting with an overview of Ontario's critical role in Canada-U.S. trade. [11]

Ontario's roads support the movement of $1.2 trillion in goods annually, which is half of Canada's total international trade and 70% of Canada's road trade with the U.S.

One of the three main Provincial border-related priorities fall into the category of infrastructure (e.g. the Gordie Howe International Bridge and the Herb Gray Parkway).

Canada's busiest border crossings are in Ontario: Windsor, Sarnia, and Ft. Erie/Niagara Falls crossings handle 59% of Canada-U.S. trade.

The U.S. is Ontario's primary trading partner. Ontario has 14 land border crossings with the U.S. In 2013, the U.S. was the destination for 80% of Ontario exports and the source of 56% of imports. Motor vehicles and parts represented the largest major commodity group accounting for 26% of Ontario's total merchandise.

3.5.3 Ontario's Freight Supportive Guidelines

"Ontario's Freight-Supportive Guidelines help municipalities better understand and plan for the vehicles that transport goods through their communities. In addition, they provide direction on how to best plan the available land, design sites and manage municipal transportation networks, to keep communities financially stable and competitive.

The document includes over 50 guidelines and almost 350 strategies to help urban planners, municipal engineers, developers and others create safe and efficient freight-supportive communities. The Guidelines include best practices and implementation strategies that apply to many communities, both urban and rural, drawing on past experiences in Ontario, North America and around the world." [12]

Efforts need to identify where rest and fuel facilities are provided along key corridors and strategies to determine optimum locations.

"Rest areas and truck stops are an important element of the Ontario road network. These facilities contribute to the safety and efficiency of freight operations in Ontario and also provide necessary amenities for truck operators to keep trucks on the road. Rest areas and truck stops also contribute to the local economy by providing jobs and generating tax revenue from sales of petroleum products and other related products.

Municipalities can encourage the development of these facilities on municipal roadways, where they do not already exist, by identifying them within their official plan or other planning documents, and by providing a zoning category and zoning by-law provisions. Municipalities should also consider opportunities to support reinvestment in rest areas at abandoned gas stations through brownfield rehabilitation. Areas for this opportunity should be identified in community improvement plans and consideration should be given to providing financial incentives to attract investment in rehabilitating abandoned sites.

Strategies

a) Identify strategic locations along freight corridors for the provision of rest area services.

b) Plan for and work to establish rest and fuel facilities for truck drivers where deficiencies are noted. Account for long combination vehicles in the design of these facilities if sites are within approximately two kilometres of a 400-series highway or equivalent.

c) Introduce signage indicating rest area information.

d) Develop informal municipal rest stops/parkettes with washroom facilities to support freight movement and tourism.

e) Coordinate with neighbouring municipalities. [**13**]

3.5.4 Existing Service Centres and Weigh Scales

It can also be stated here that there are many existing refuelling/service centres in the province of Ontario with many locations supporting the freight industry traveling along the 401/QEW corridor. ONroute operates 20 centres with specific locations [**14**] and Pilot Flying J operates out of 17 locations [**15**] that are all strategically located at primary locations. Allstays provides details on various truck stop locations and weigh scale locations. [**16**], [**17**]

In summary, along the 401/QEW corridors weigh scales are located at 401 - Lakeshore (Essex), 401 – Thames Centre (London), 401 - Milton, 401 - Whitby, 401 - Clarington, 401 - Landsdowne (Gananoque), 401 - Lancaster, QEW – Fort Erie, QEW - Beamsville, QEW - Stoney Creek. Two others of note include 402 – Wyoming (near Sarnia), 403 – Brantford, and 403 – Oakville.

An interactive map maintained by the Ministry of Transportation of Ontario shows all weigh scale locations in a macro or micro or detailed location level. **FIGURE 3.6** shows a macro view.

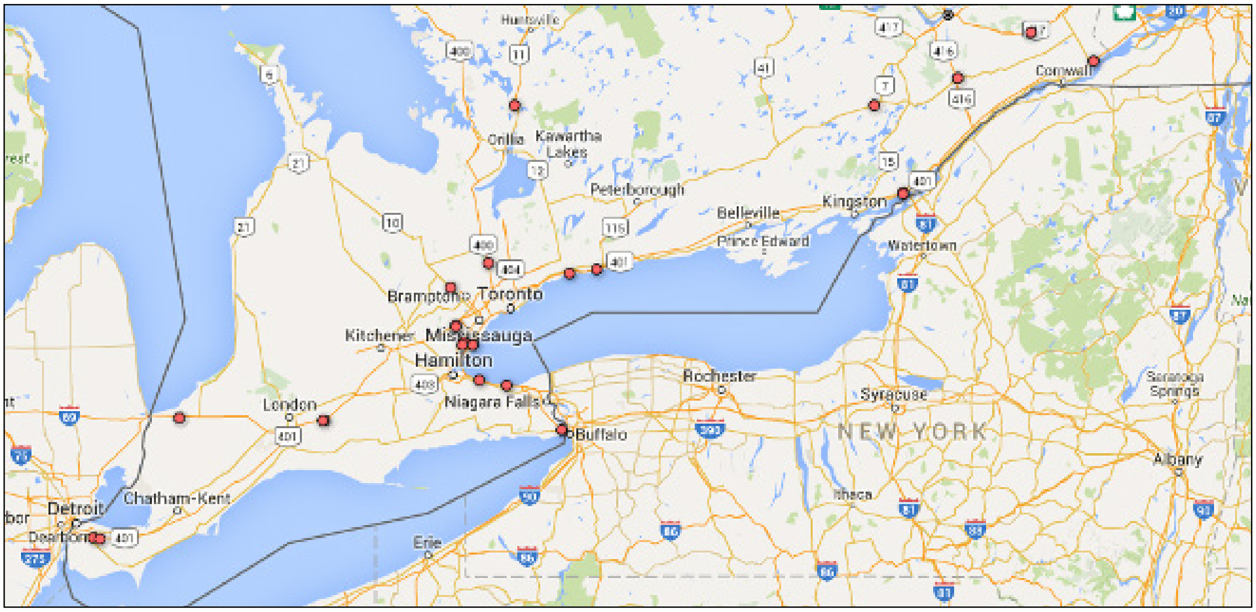


FIGURE 3.6 Ontario Truck Inspection Stations – Southern Ontario

3.5.5 Ministry of Transportation of Ontario Overview Information

In Ontario, the Ministry of Transportation (MTO) iCorridor service provides general information on land use planning, road travel speed and performance indices, transportation planning and forecasting, provincial highway information and multi-jurisdictional collaboration. Within the transportation planning and forecasting activity some Commercial Vehicle Traffic Volumes, Equivalent Single Axle Load and results of the Commercial Vehicle Survey program information is available. **FIGURE 3.7** illustrates the basic high-volume traffic flow Average Annual Daily Truck Traffic. [**18**]

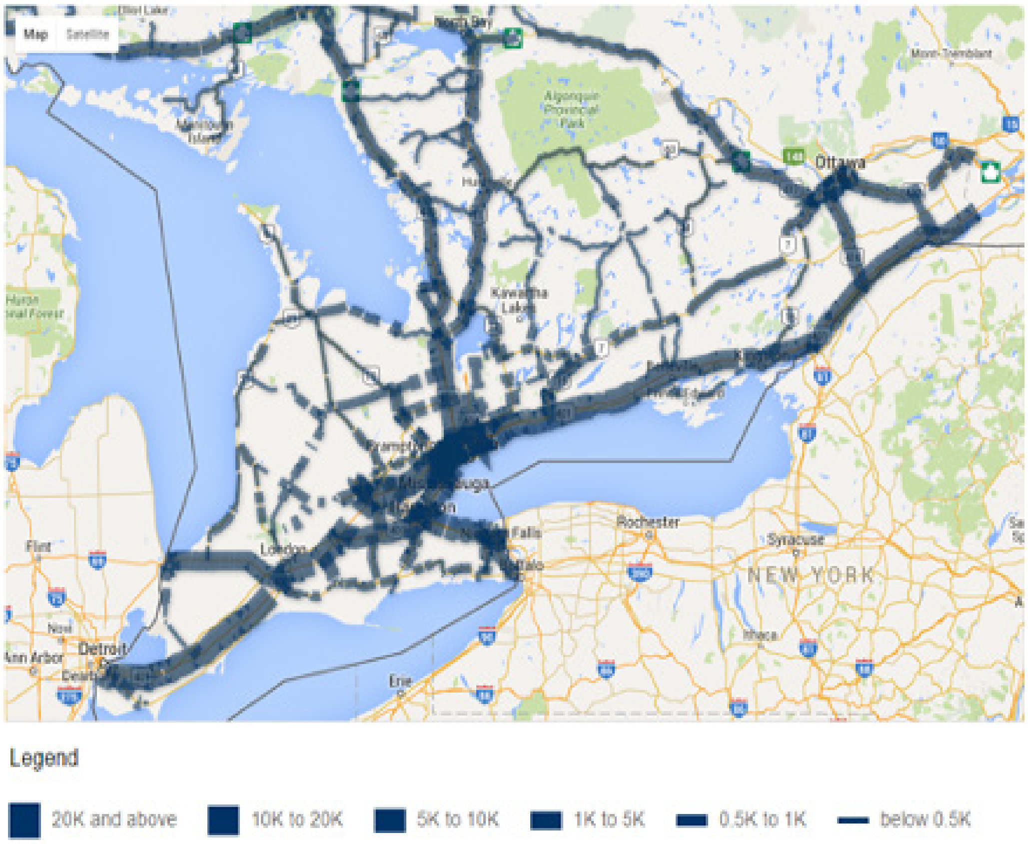


FIGURE 3.7 2008 Commercial Vehicle Traffic Volume

In Ontario, the Ministry of Transportation monitors the condition of commercial motor vehicles operating in Ontario. Vehicles and loads are checked for weight, height, length, width, and axle spacing at various inspection stations across the province.

MTO's Road User Safety Division operates 49 Truck Inspection Stations (directional) across Ontario where permanent facilities exist to support inspection duties for extended purposes and generally have a scale in operation. Specifically, there are five Truck Inspection Stations on the 401 and five on the QEW (directional).

They also conduct regular Commercial Vehicle Surveys (CVS) where weight station data is captured for detailed analysis. In general, MTO conduct the CVS at about 200 directional survey sites in a 3-year cycle. The last two surveys were conducted in 2006 and in 2012.

MTO is migrating into a continuous data collection strategy for the CVS starting in 2017. As part of this strategy, intent is to report every year with an 8-month lag between data collection and public reporting. Thus, MTO is planning to have an update in 2018, but the new approach may involve concentrated data collection in regions of interest and as such may not represent a province wide update annually.

To better understand the overall Ontario MTO CVS survey process and summary results that come from that activity please refer to a presentation titled: FHWA Ontario Commercial Vehicle Border Survey Workshop, TBWG - Trade and Traffic Data Session, October 27, 2015. [19]

3.5.6 Trend Analysis of Ontario Border Crossing Volumes

During a Border Survey Trade and Data Session conducted during the 2012 Transportation Border Group Plenary Session in Ottawa in 2012, Rob Tardiff from the Ontario Ministry of Transportation reported truck volumes peaked in year 2000 at 8.6 million and a reached a low of 6 million crossings in year 2009 which represented a decline of 29%. In 2011, truck volumes increased to 6.7 million or 10% from the low point in 2009. [20]

FIGURE 3.8 illustrates the forecasted impact of additional truck trips in Ontario and Quebec by 2026. MTO analyses shows for 2006 Ontario tracked about 150,000 daily trips which is forecasted to increase by 100,000 to 252,000 by 2026. In Quebec 80,000 daily trips in 2006 are forecasted to increase by an additional 55,000 to 135,000 daily trips.

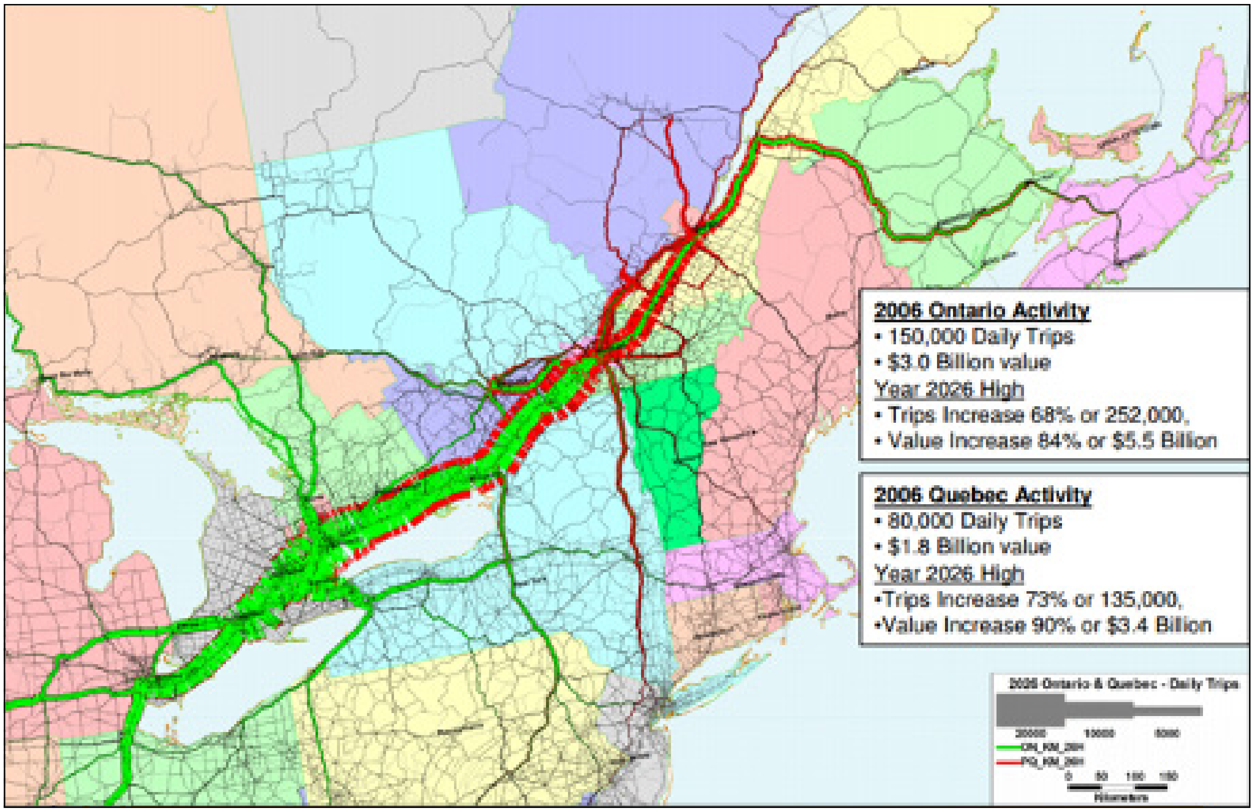


FIGURE 3.8 2026 Ontario-Quebec Truck Trips

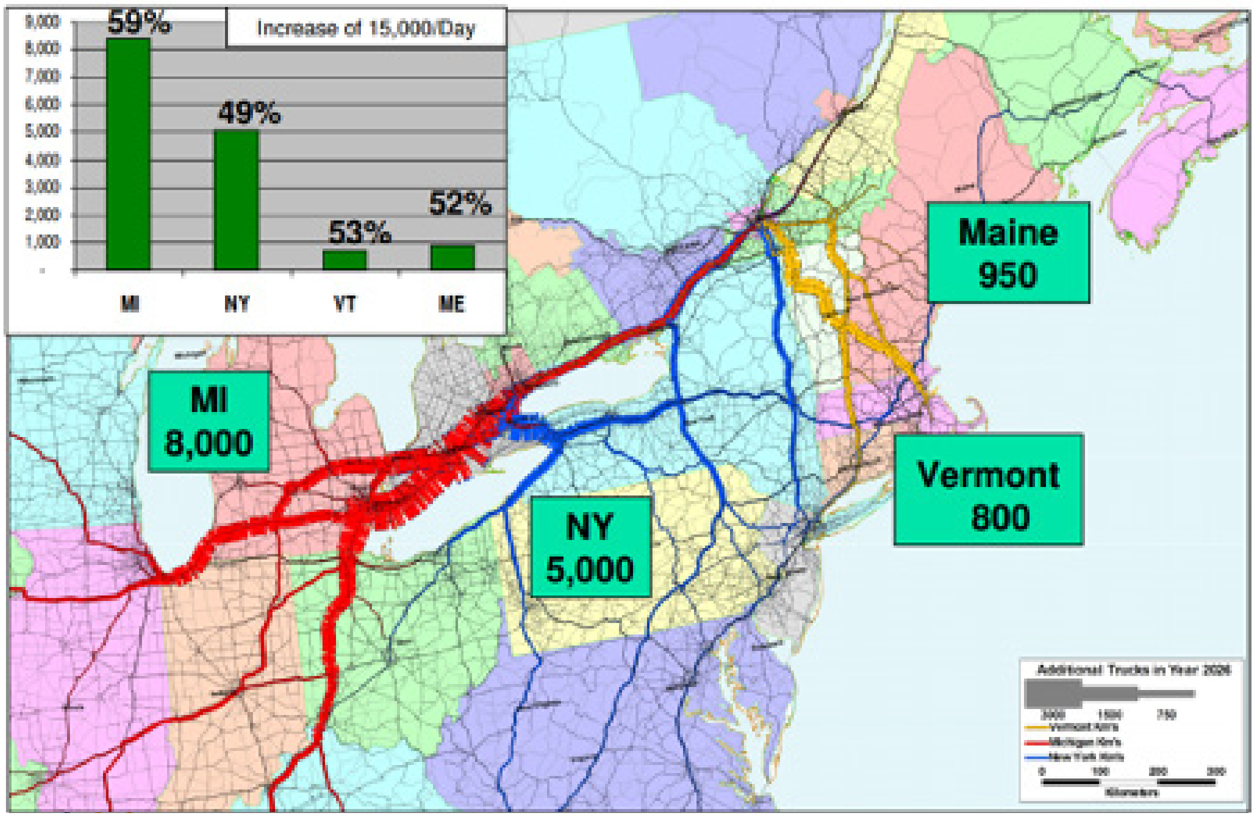


FIGURE 3.9 Forecasted Additional Daily Trucks at U.S. State Border Crossings (2006-2026)

FIGURE 3.9 illustrates the forecasted additional U.S. State border crossings between 2006 to 2026. The total increase presents an additional 15,000 crossings per day with each of the crossing points showing a percent increase from 49% to 59% across the four crossing points. The details illustrate Michigan and New York being the largest corridor crossings.

The iCorridor reference also provides a simple interactive illustration forecasting Equivalent Single Axle Loading by comparing 2006 versus 2026 along all major highways in the province. It provides an easy and simple method to get a feel for all type of truck traffic regardless of Class of tractor or number of tractor/trailer axles. It also helps illustrate which corridors will see the most significant rate of change looking into the future.

FIGURE 3.10 shown below is a macro snapshot to help illustrate how this information is displayed for additional study. [21]

FIGURE 3.11 provides a more detailed visualization of anticipated loading along the major freight highways. One can go as deep into the data to expand what might be excepted as one travels through any region or community.

The MTO, through their Systems Analysis and Forecasting Office (SAFO), using a Provincial Highway Forecasting Tool, project the Level of Service (LOS) along major provincial highways.

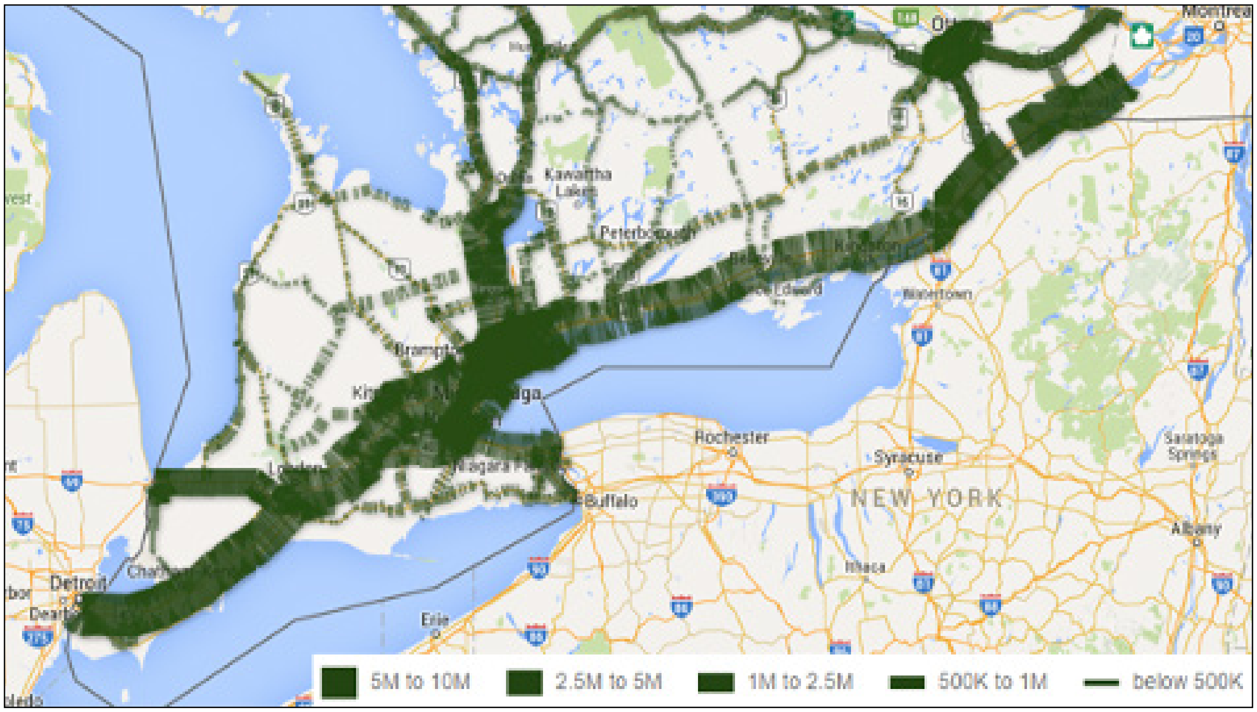


FIGURE 3.10 Equivalent Single Axle Load, 2026

SOURCE: ONTARIO MINISTRY OF TRANSPORTATION

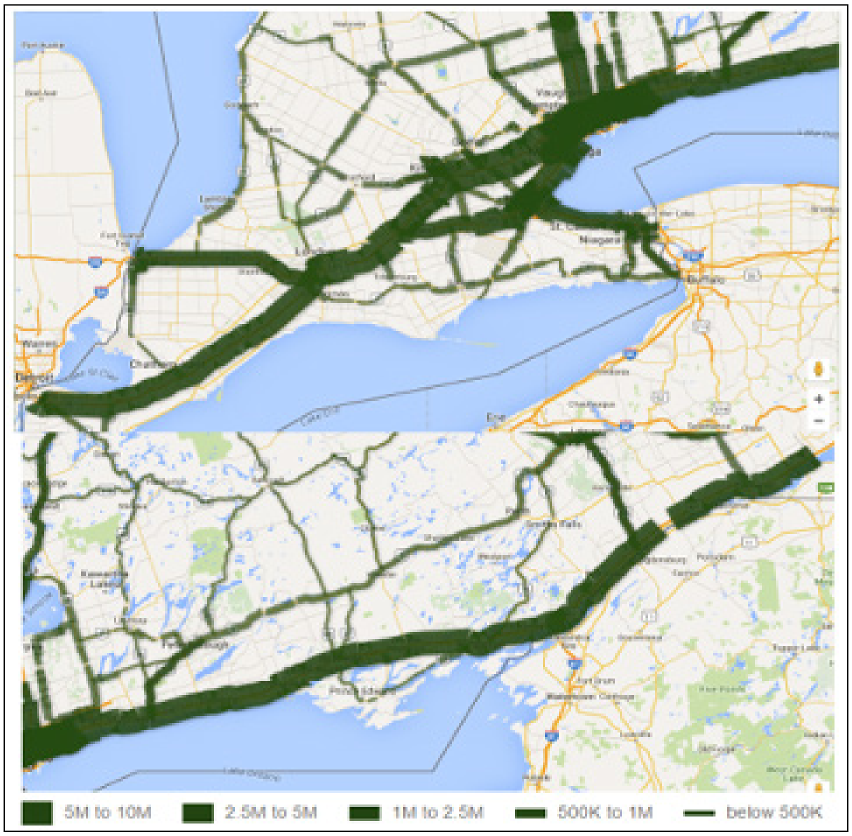


FIGURE 3.11 Equivalent Single Axle Load: West and East Corridors – 2026

SOURCE: ONTARIO MINISTRY OF TRANSPORTATION

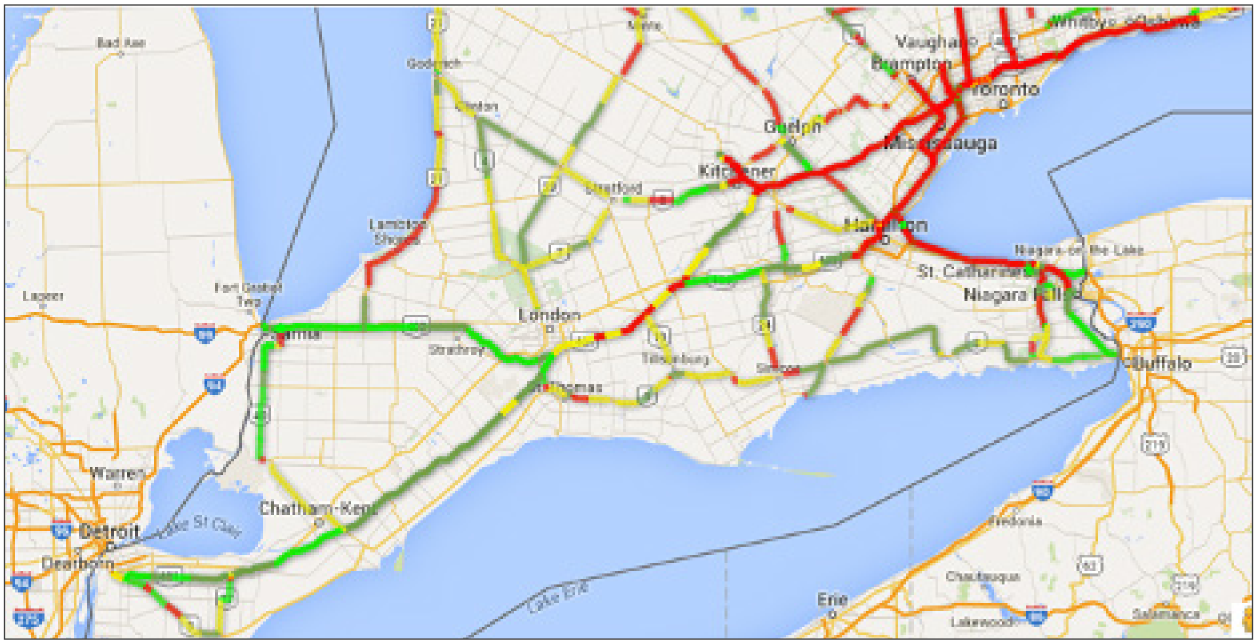


FIGURE 3.12 West Corridor — Level of Service, 2031

SOURCE: ONTARIO MINISTRY OF TRANSPORTATION

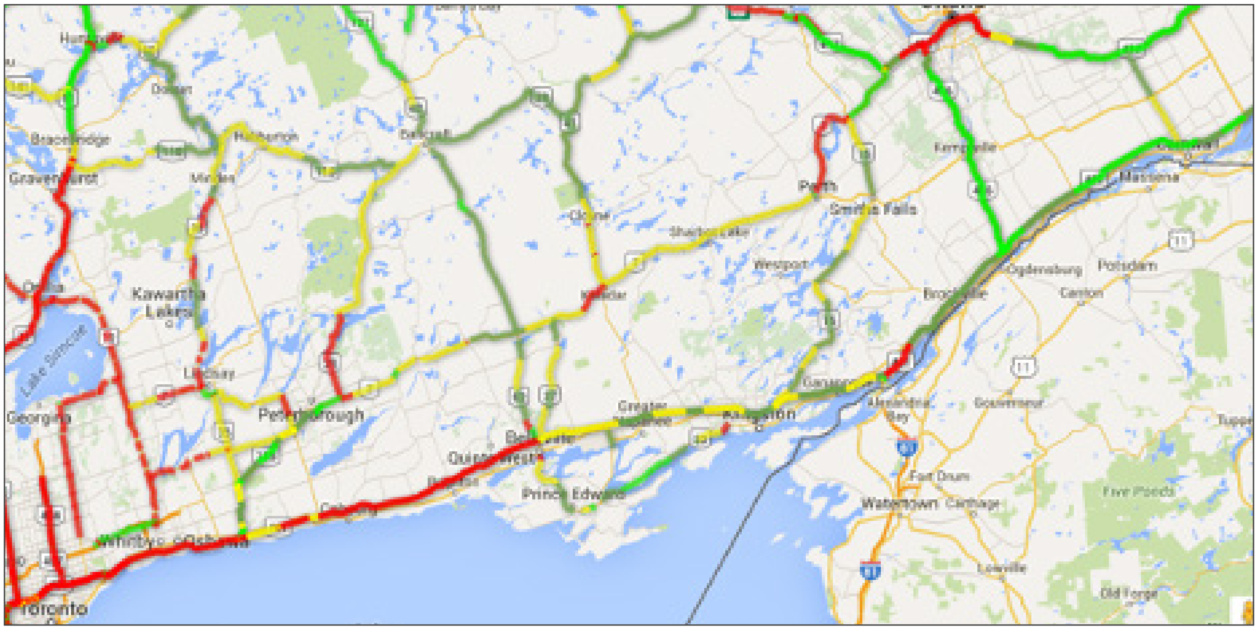


FIGURE 3.13 East Corridor — Level of Service, 2031

SOURCE: ONTARIO MINISTRY OF TRANSPORTATION)

FIGURE 3.12 and **FIGURE 3.13** helps illustrate potential future freight movement bottlenecks. It is very clear that the QEW, 401 from Kitchener to Oshawa and Cobourg to Belleville showing red will remain a challenge. Routes that are considered red might be prime targets for additional rest stations, vehicle charging and or fuelling stops for diesel, CNG or hydrogen that could support drivers and the efficient, safe and convenient movement of goods that they are transporting.

3.5.7 McMaster Institute for Transportation and Logistics

The McMaster Institute for Transportation and Logistics has conducted two very relevant studies that were reviewed and referenced here in support for this report namely: Truck Freight Generators and Attractors in the Province of Ontario (March 2014) [22] and Estimating Urban Commercial Vehicle Movements in the Greater Toronto and Hamilton Area (GTHA) (July 2010). [23] Some of the material from these reports is presented here to help provide a framework for defining hydrogen powered vehicles and hydrogen refuelling station siting considerations.

Some additional information contained in these source documents are not included but highlighted here to help create awareness, namely:

- Prevalence of Commodity Types Carried by Truck in Ontario
- Distribution of Truck Trips by Commodity Type and MTO Region

FIGURE 3.14 illustrates Class 3 to 8 commercially registered vehicles in operation based on the 2011 census subdivision in which they are registered. Although one cannot draw conclusions as to where they operate or fuel their vehicles it does offer a relative indication of potential home basis.

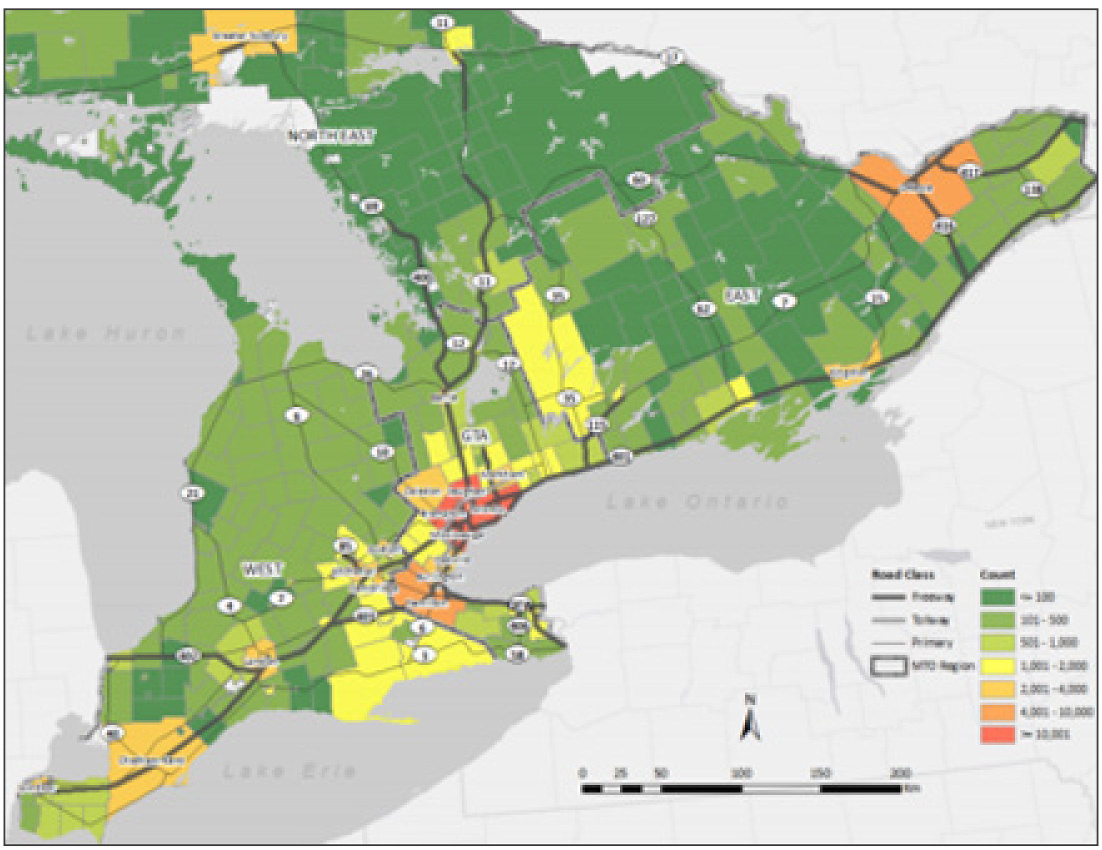


FIGURE 3.14 Class 3 to Class 8 Commercial Vehicles in Operation by Municipality (2011)

SOURCE: MCMASTER INSTITUTE OF TRANSPORTATION AND LOGISTICS

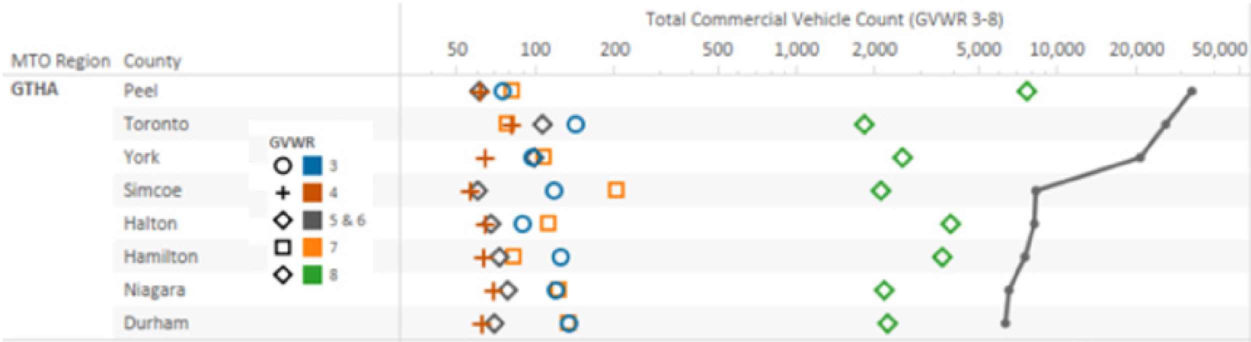


FIGURE 3.15 Commercial Vehicles in Operation by GVWR Class and Geography – GHTHA

SOURCE: MCMASTER INSTITUTE OF TRANSPORTATION AND LOGISTICS

FIGURE 3.15 in an extract from Figure 3-11 in the cited source, provides a summary of these registrations by county. These classes cover the medium and heavy range of vehicles by GVW. About 54% of the total Class 3-8 registrations in Ontario belong to the largest Class 8 vehicles. Approximately 63% of Peel's registrations are in the Class 8 category which is notably higher than other counties in the GTA. [**24**]

The use of Annual Average Daily Trucking Volumes along certain highway sections is a very good method to not only track vehicles on the road but also help plan highway development, rest and refuelling stops. This can obviously also then be used for planning future deployments of hydrogen powered vehicles and a hydrogen fuelling infrastructure to support Class 8 trucks.

FIGURE 3.16, **FIGURE 3.17** and **FIGURE 3.18** is included in this report to illustrate the traffic volume. Figures illustrate volume with different colours. Without going into too much detail, it is apparent that yellow bars (5,001 and 10,000 trucks), light orange (10,001 and 15,000 trucks), dark orange (15,001 and 25,000 trucks) and red (above 25,001 trucks) represent segments of the highway resulting in the most freight traffic across major Ontario highways, as examples. [**25**]

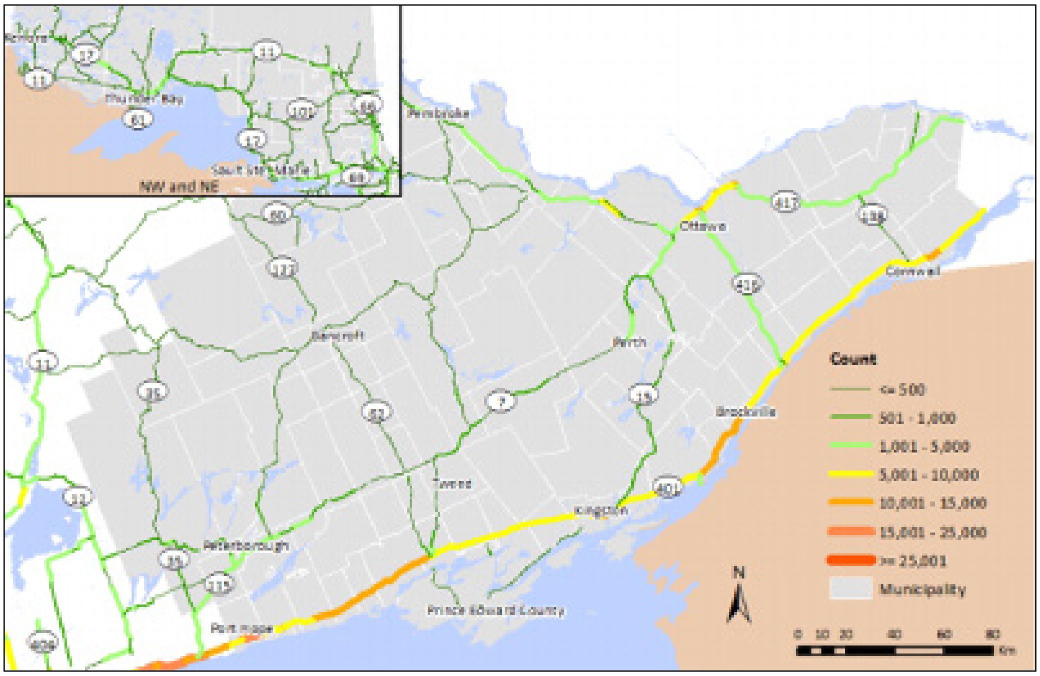


FIGURE 3.16 Annual Average Daily Trucking Volumes: East

SOURCE: MCMASTER INSTITUTE OF TRANSPORTATION AND LOGISTICS

FIGURE 3.17 Annual Average Daily Trucking Volumes: West

SOURCE: MCMASTER INSTITUTE OF TRANSPORTATION AND LOGISTICS

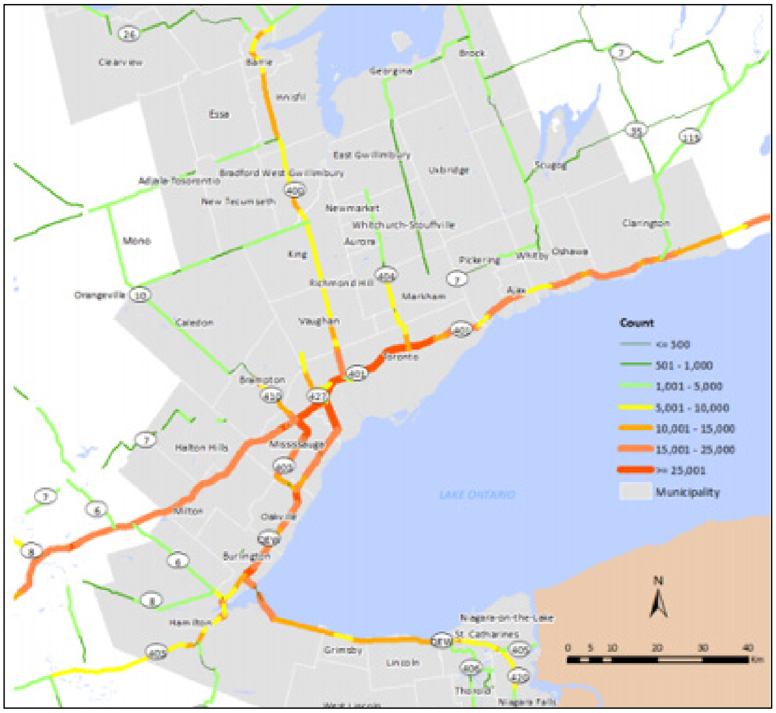


FIGURE 3.18 Annual Average Daily Trucking Volumes: GTA

SOURCE: MCMASTER INSTITUTE OF TRANSPORTATION AND LOGISTICS

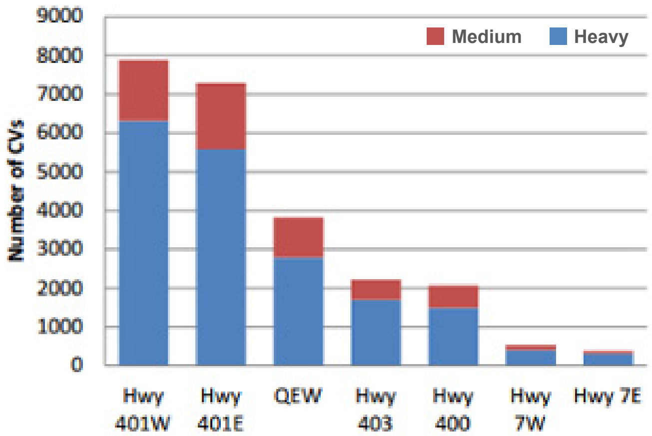


FIGURE 3.19 Gateway Used to Exit GTHA for Internal-External Trip (by truck type)

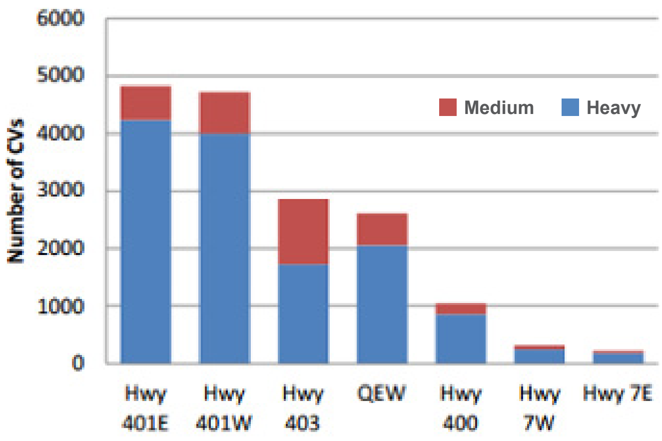


FIGURE 3.20 Gateway used to enter GTHA for a Pass-thru trip (by truck type).

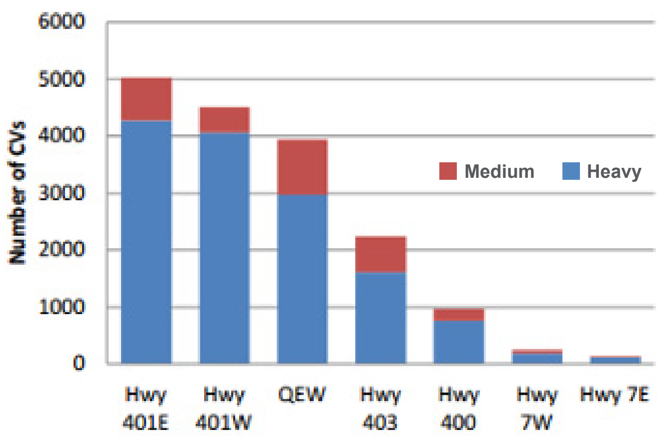


FIGURE 3.21 Gateway used to exit GTHA for a Pass-thru trip (by truck type.

SOURCE: MCMASTER INSTITUTE OF TRANSPORTATION AND LOGISTICS.

FIGURE 3.19 shows the number of heavy and medium internal-to-external trips exiting at various gateways out of the study area. In all cases, the majority of Commercial Vehicles (CVs) are heavy, and the higher proportion of heavy CVs becomes more evident on the lower volume gateways.

As expected, the 401E and 401W gateways handle a disproportionately high volume of exiting CV traffic. The QEW, Highway 403 (towards Brantford), and Hwy 400 play important secondary roles. [**26**]

FIGURE 3.20 and **FIGURE 3.21** Gateway used to exit GTHA for a Pass-thru trip (by truck type) show the volumes of heavy and medium CVs making Pass-through trips, as they enter and exit the study area, respectively.

As in **FIGURE 3.19**, most Pass-through trips are made by heavy CVs, and the 401E and 401W gateways tend to contain the highest volumes of trips. It is interesting to note that the QEW is relatively more important for pass-through trips that are exiting the GTHA as opposed to entering it. [**27**]

3.5.8 Ontario – 2006 and 2012 MTO Commercial Vehicle Survey Data and Analysis

MTO is migrating into a continuous data collection strategy for the CVS starting in 2017. As part of this strategy, intent is to report every year with an 8-month lag between data collection and public reporting. Thus, MTO is planning to have an update in 2018, but the new approach may involve concentrated data collection in regions of interest and as such may not represent a province wide update annually.

With the support of the MTO, specifically Rob Tardif, the author was able to review some of their analysis and received special access to some of their raw data files to conduct application specific analysis.

To better understand the overall Ontario MTO CVS survey process and summary results that come from that activity please refer to a presentation titled: FHWA Ontario Commercial Vehicle Border Survey Workshop, TBWG - Trade and Traffic Data Session, Oct. 27, 2015. [28]

A forward-looking opportunity at the nature of future data offers an opportunity to do more advanced data analytics against the data sets collected by MTO an studies leveraging this data through the McMaster Institute of Transportation Logistics in the future to even better explore CNG refuelling opportunities.

3.5.9 Ontario Growth Plan 2016

The Ontario Minister of Municipal Affairs and Housing have been working on a proposed Growth Plan for the Greater Golden Horseshoe (2016). In May details were released for public review and comments. [29]

It is recognized that "Increased traffic congestion, and the resulting delays in the movement of people and goods in the GGH, is costing billions of dollars in lost GDP every year." [30] As part of this plan there are specific strategies titled "Infrastructure to support growth - moving goods and infrastructure corridors)." [31] See FIGURE 3.22 to illustrate considerations for future transportation corridors and highway extensions.

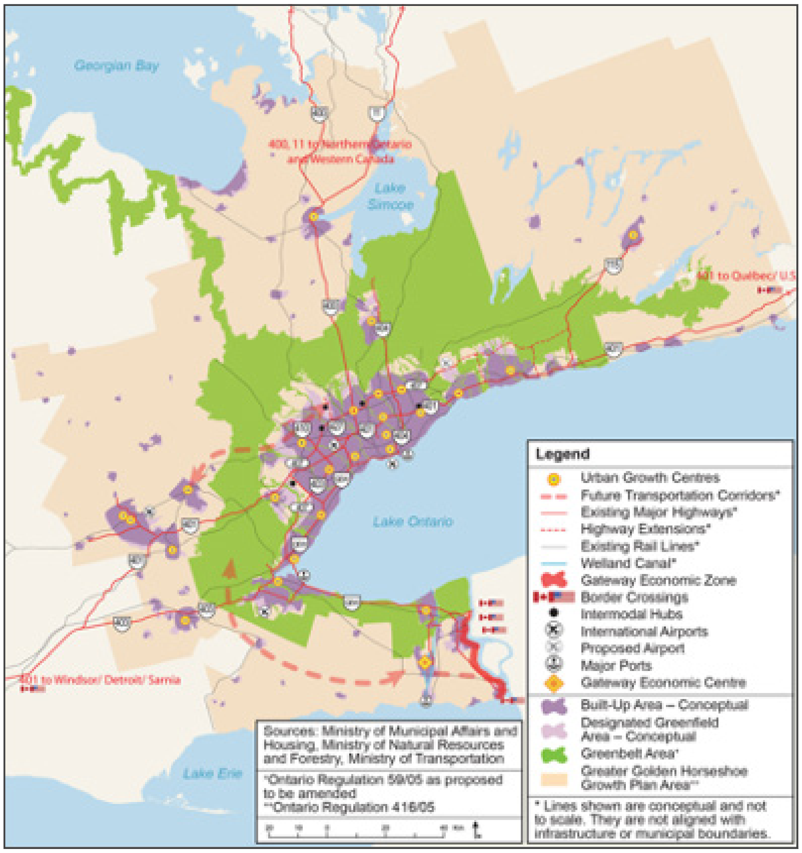


FIGURE 3.22 Grow Plan – Schedule 6 - Moving Goods

SOURCE: ONTARIO MINISTRY OF MUNICIPAL AFFAIRS AND HOUSING

Greater Toronto Area West Corridor Project

The Ministry of Transportation has also been working on an environmental assessment of the Greater Toronto Area West Highway Corridor (GTA West). This project was suspended in December of 2015 and an update was to be expected in the spring 2016. Given its status, no consideration to this study was assessed. [**32**]

FIGURE 3.23 illustrates the general study area where a 4 to 6 lane corridor is being proposed northwest of Toronto and highway 407 from Georgetown to highway 400 with connections to highway 410. [**33**]

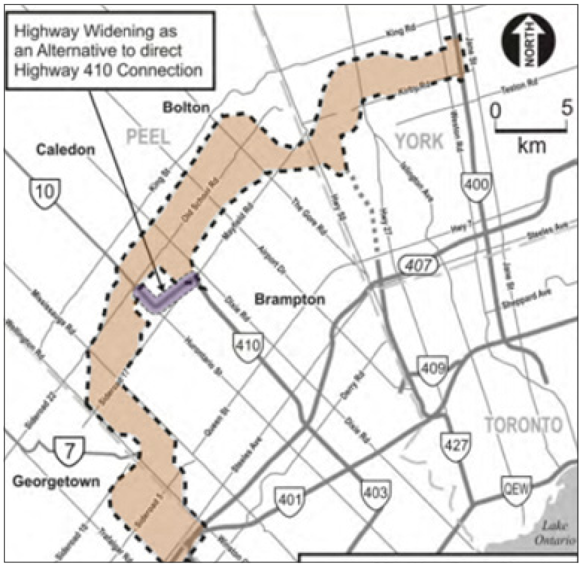
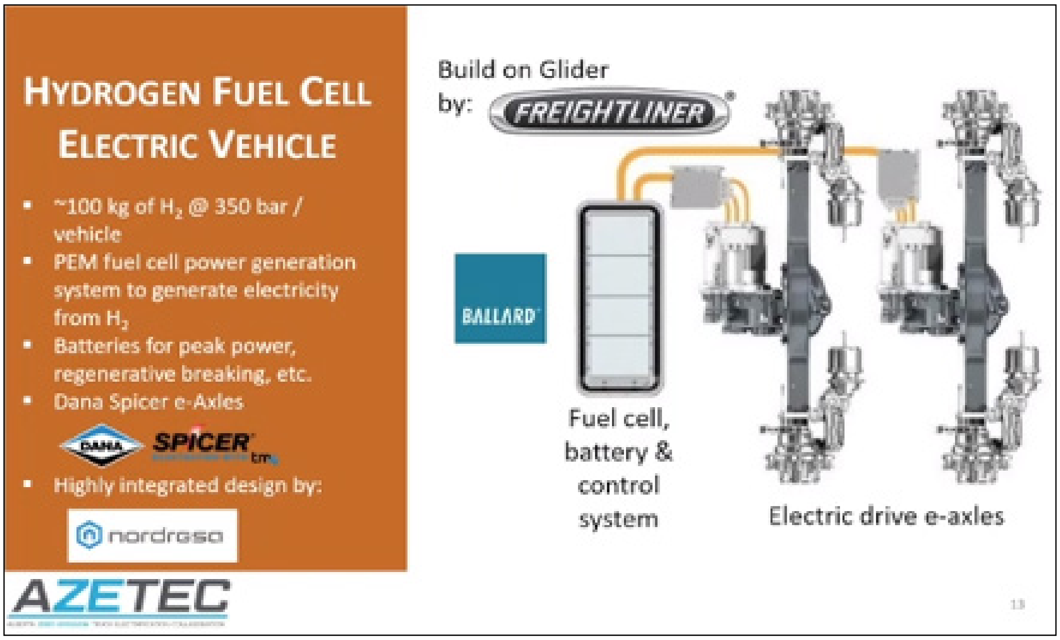


FIGURE 3.23 GTA West Route Planning Study Area
SOURCE: ONTARIO MINISTRY OF TRANSPORTATION

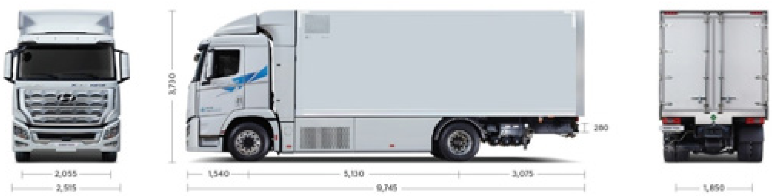
3.6 Class 8 Vehicles - Available Hydrogen Capable Powertrains

For an extensive report with details surrounding the state of hydrogen powered vehicle technology readers are encouraged to review *Survey of heavy-duty hydrogen fuel cell electric vehicles and their fit for service in Canada*, Transition Accelerator Reports, Volume 2 – Issue 1, July 2020.[5]



HTTPS://360ENERGY.NET/EMISSIONSFREETRUCKING/ (ACCESSED, 26 APRIL 2021)

5 https://transitionaccelerator.ca/survey-of-heavy-duty-hydrogen-fuel-cell-electric-vehicles-and-their-fit-for-service-in-canada/



Powertrain	
Fuel Cell Stack	190 kW (95 kW x 2 EA)
Battery	661 V / 73.2 kWh – by Akasol
Motor / Inverter	350 kW / 3,400 Nm – by Siemens
Transmission	ATM S4500 – by Allison / 6 forward speeds and 1 reverse speed
Rear Axle ratio	4.875
Hydrogen Tank	
Filling Pressure	350 bar
Capacity	32.09 kg H2 (available hydrogen amount at SOF 100%)

Hyundai product[6]

- World's First Fuel Cell Heavy-Duty Truck, Hyundai XCIENT Fuel Cell, Heads to Europe for Commercial Use
- Hyundai Motor is shipping the first 10 units of XCIENT Fuel Cell, the world's first fuel cell heavy-duty truck, to Switzerland
- Hyundai will roll out 50 trucks this year and total of 1,600 units by 2025
- Powered by 190-kW hydrogen fuel cell system, XCIENT Fuel Cell can travel approximately 400 km on a single charge
- Developed independently by Hyundai Motor, XCIENT Fuel Cell will help decarbonize the world
- Hyundai to develop tractor unit with driving range of 1,000 kilometres on a single charge

6 https://www.hyundainews.com/en-us/releases/3081 (Accessed, 26 April 2021).

3.7 HD Truck – Hydrogen Refuelling Needs – Ontario-Quebec Freight Corridor

The history and development of CNG and LNG refuelling systems in Canada is not explained in detail. It is recognized that CNG and LNG infrastructure exists in both Canada and the USA. The writer will only focus on current CNG stations and the potential needs and outlook as it relates to the Ontario-Quebec freight corridor and how that can influence the selection of hydrogen-fuelled heavy duty trucks and the location of hydrogen refuelling.

3.7.1 Comparison of Vehicle Range with CNG and Hydrogen Tank Packages

In order to begin to understand CNG and hydrogen refuelling needs to support Class 8 trucks one does need to have a basic understanding of vehicle and onboard vehicle fuel storage configurations. By way of example one can consider what is offered by various vehicle manufacturers with the application of Cummins-Westport powertrains.

The primary configurations of CNG fuel storage systems for heavy-duty trucks consist of Side Mount Rail mount (SMR) and Behind the cab (BTC).

The side mount rail mount system is like diesel fuel tanks in appearance as it is mounted to the frame rail of the truck under the cab. The fuel capacity of a CNG side mount system ranges from 17-60 DGE per side.

BTC systems are installed behind the cab of the truck and require at least 22 inches of frame rail space. The fuel capacity of CNG BTC tank systems range from 15 to 160 DGE.

FIGURE 3.24 illustrates example Agility Fuel System installations and Momentum Fuel Technologies CNG Fuel Storage Modules. [34], [35]

A vehicle's fuel capacity can be increased by packaging the side mount system on the driver side of the vehicle with another side mount system on the other side of the vehicle and/or with behind the cab system configuration. Using his approach for CNG given today's offerings can provide capacity of up to 286 DGE. With a typical fuel consumption for a truck equipped with a 12L CWI engine being in the range of 5 mpg, the maximum range with the combined BTC and SM tanks amounts to 1900 – 2200 km (1200 – 1400 miles).

Commonly, CNG trucks carry enough CNG for about an 800 km (500 mile) range, but drivers frequently want enough fuel for more than one day's driving to avoid too many stops at filling stations. In these cases, CNG storage for a 1300 km (800 mile) range is quite feasible with BTC storage.

As the information presented illustrates, CNG system designers and integrators are offering a variety of vehicle range options (CNG storage systems) based on customer needs and their likely duty cycle (range, proximity and access to CNG refuelling).

Given the variety of systems that can be specified by fleets the ability to match refuelling stations location based on carrier requirements and truck operating range is a very complex problem to accurately predict without detailed insights surrounding freight movement and carrier operating practices.

FIGURE 3.24 Behind the Cab and Side Mount Rail CNG Fuel Storage System

Hyundai recently announce the worlds first commercial fuel cell truck with 32 kg of hydrogen on board with a range of 400 km on a single charge of fuel. They are working on expanding the capability to 1000 km (likely with the use of multiple 700 bar (70 MPa) storage cylinders.

3.7.2 Current and Planned CNG Infrastructure (Case Study) to Guide Future Hydrogen Vehicles and Infrastructure

The application of the process described below as it relates to CNG could be applied in the future when considering the planned and deployed locations of hydrogen refuelling stations. At this point there are NO HD truck capable hydrogen refuelling stations being contemplated, planned, funded or in operation in eastern Canada.

3.7.3 United States

The heavy-duty trucking sector is gaining momentum. Recently it appeared that CNG over LNG is being favoured as the fuel for Class 8 regional and long haul trucks because it is possible to get sufficient range on CNG with up to 280 DGE (diesel gallons equivalent) of fuel storage, and the CNG system is easier to use. Also, increasingly, long distance trucking is changing from patterns where a single vehicle with a single driver tranverses the entire country to a hub-and-spoke operation where more localized fleets handle part of a longer journey for modular containers.

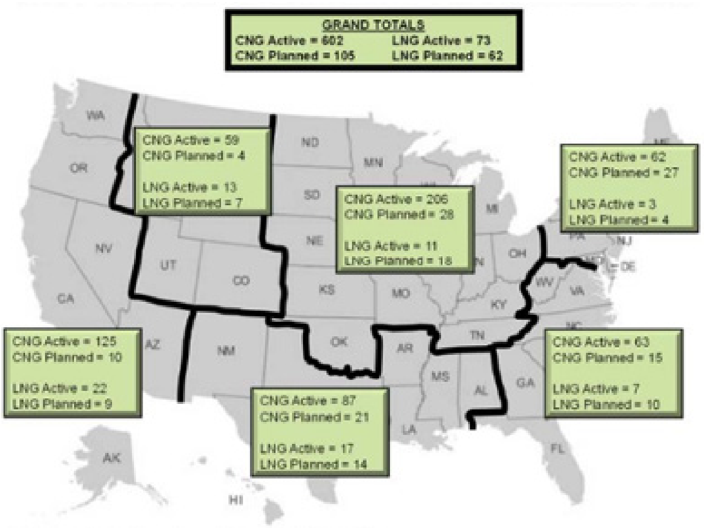


FIGURE 3.25 U.S. Public HD NG Stations by Region (June 2015)

SOURCE: U.S. DOE

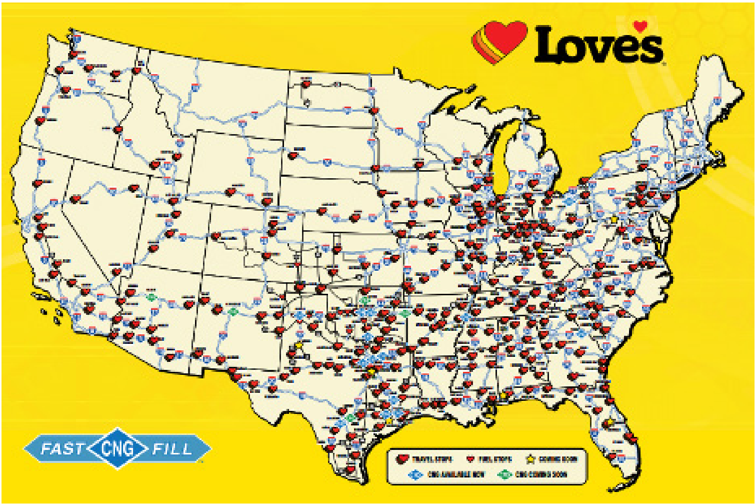


FIGURE 3.26 Love's Truck Stops/Travel Stores showing CNG Stations

FIGURE 3.27 Gain U.S. CNG Stations – Northeast U.S. Focus

FIGURE 3.25 shows the status of the U.S. CNG and LNG refuelling station infrastructure as of June 2015, and suggests there are 602 active CNG stations across the U.S. with additional details illustrating the number per region. [36]

Much of the build out of recent new CNG stations has been carried out at truck stops. As an example, Kwik Trip currently has about 32 CNG stations [37] and Love's Truck Stops and Travel Stores recently opened their 17th CNG station. [38] FIGURE 3.26 illustrates the Love's Locations that currently provide CNG refuelling capability. [39]

CNG's presence at U.S. fuel retailers is also growing based on Gain U.S. investment in CNG refuelling stations.

FIGURE 3.27 illustrates approximately a half dozen CNG stations relatively close and along truck routes supporting Ontario and Quebec freight traffic. Map also highlight two existing stations in Ontario and Quebec described more later in this report. [40]

FIGURE 3.28 and FIGURE 3.29 may help illustrate the current aggregate state of CNG stations and a built out forecast as reported by NGVAmerica. [41] The confidence in this planned rollout and the timeline and assumptions under which these maps have been created has not been assessed. They are shown to provide a general indication of the relative numbers of new CNG stations being foreseen and the area of the country where they might show up. It appears as future growth for the CNG station is in the northeast, southeast and east Texas area.

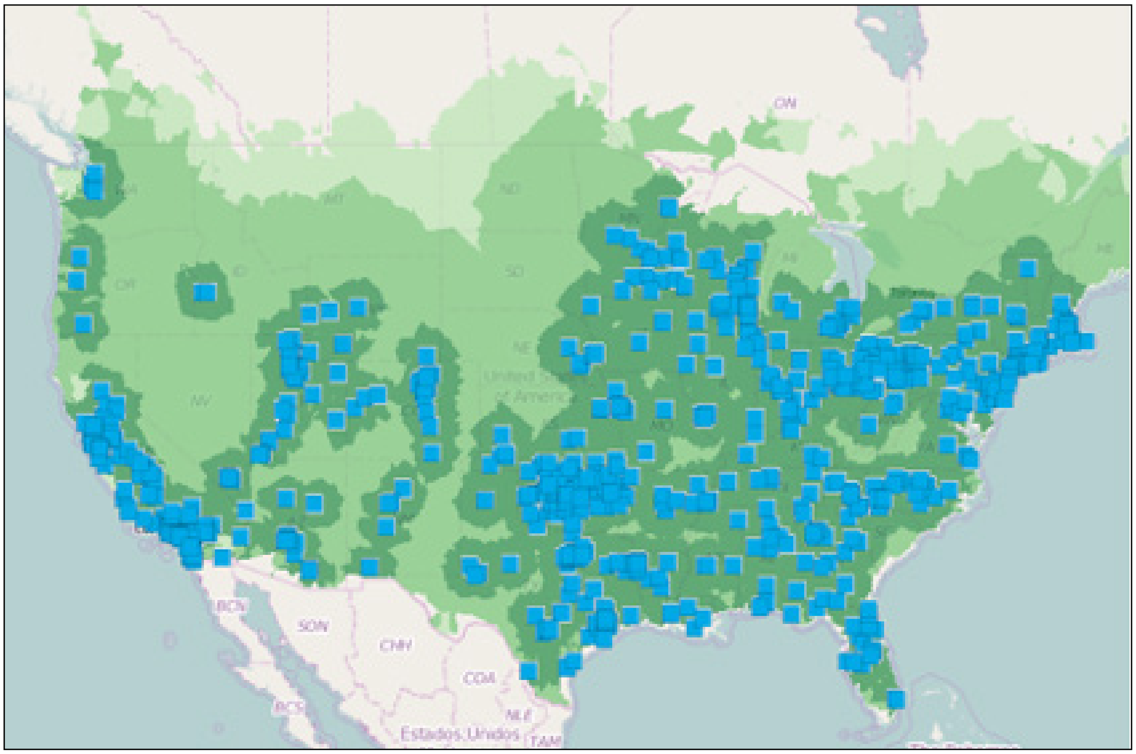


FIGURE 3.28 U.S. CNG Stations - Existing

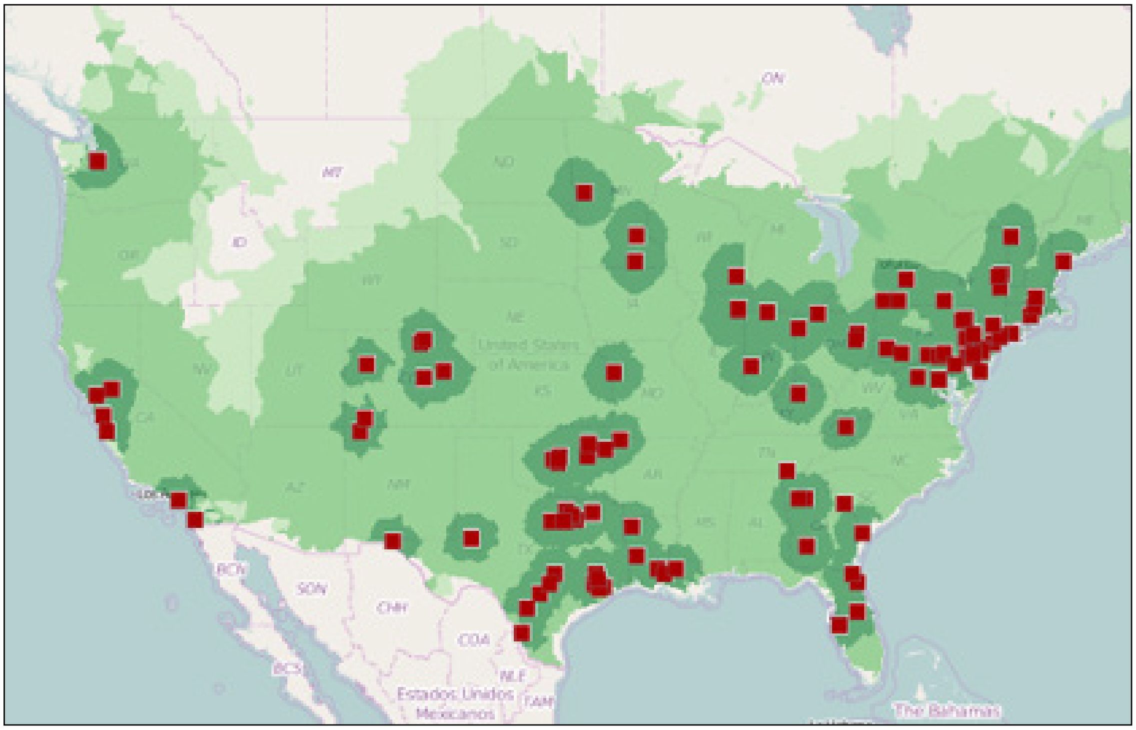


FIGURE 3.29 U.S. CNG Stations - Planned

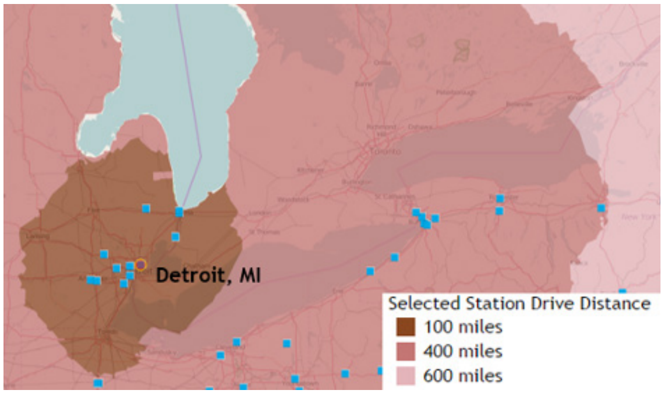


FIGURE 3.30 Location from Detroit, MI – 100, 400, 600 Mile Reach

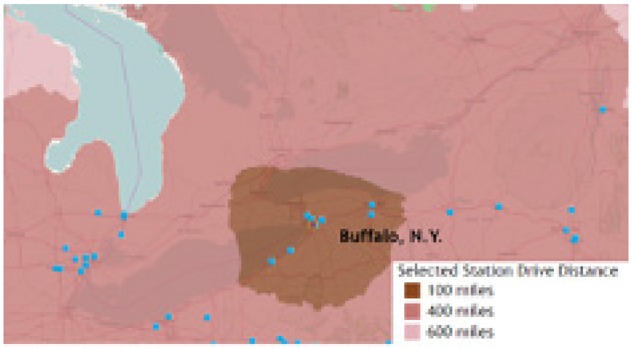


FIGURE 3.31 Location from Buffalo, NY – 100, 400, 600 Mile Reach

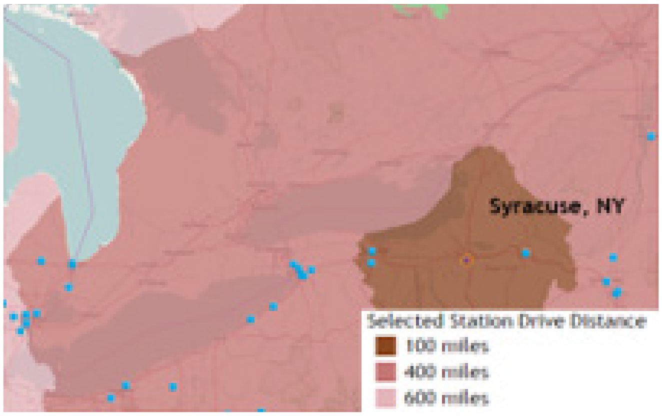


FIGURE 3.32 Location from Syracuse, NY – 100, 400, 600 Mile Reach

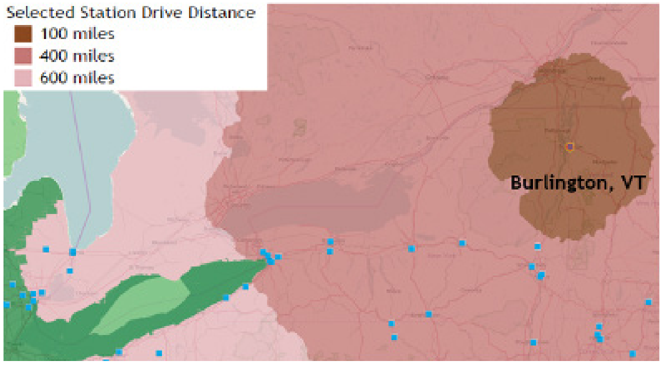


FIGURE 3.33 Location from Burlington, VT – 100, 400, 600 Mile Reach

The proximity and growth of U.S. CNG stations suitable to support trucks operating along the major north south corridors and into Ontario and Quebec, whether they are U.S. or Canadian carriers, is difficult to fully assess.

In focusing on some of the stations shown within a reasonable range from Ontario and Quebec border crossing points can offer some indications of where freight carriers might see existing refuelling infrastructure to utilize and where "range anxiety" might suggest general areas to strategically place additional CNG infrastructure along the Ontario/Quebec freight corridors.

FIGURES 3.30, 3.31, 3.32 and **3.33** each show approximate end range boundary based on a 100-, 400- and 600-mile driving distance from existing CNG refuelling stations closest to the Ontario and Quebec borders located in Detroit, Mich.; Buffalo, NY; Syracuse, NY; and Burlington, VT respectively.[**42**] This can provide an approximate indication of where the maximum or optimistic driving reach is achievable. This can also guide where refuelling might be strategically located to manage carrier and driver "range anxiety" to their end destination, limits to support a return journey or refuelling as part of a way point or rest stop.

It must be stated that heavy-duty trucks that are refuelling further south in the U.S., away from the Ontario and Quebec border points, will in fact open up more geography in Ontario and Quebec for strategic refuelling placement.

In studying this information, as well as the range estimates based on typical Class 8 CNG trucks with typical CNG ranges of CNG storage on board CNG tractors, would suggest that a 200 - 400-mile distance between stations might be most attractive to support CNG heavy truck traffic. This could support refuelling for through traffic / way points and could also be located near "ship to" or "ship from" hubs.

The author has not studied the density and proximity of various existing CNG stations in the U.S. or attempted to explore if other studies or literature might provide insights to distance between stations to best satisfy Class 8 truck market development.

3.7.4 Canada – Ontario and Quebec Focus

The growth of NGV infrastructure to support CNG vehicles in Canada has been very small compared with the U.S. and many other regions globally. Predominantly CNG was initially deployed to serve a light and medium duty market. There is an existing limited heavy-duty market operating on LNG but no known expansion of engine technology or LNG refuelling infrastructure to support higher horsepower needs.

With the departure of the Westport HPDI LNG engine, and the emergence of the CWI 12L engine capable of serving the Class 8 heavy-duty truck market, there has been a shift trending to favour CNG as the predominant fuel.

Recently, Canadian waste management company Emterra Group in partnership with fuel supplier GAIN Clean Fuel and transportation company C.A.T. Inc. have opened the first public CNG fuelling station in Mississauga, ON. [**43**] C.A.T. Inc., based in Quebec, provides cross border trucking services between Canada and the U.S., running Class 8 trucks from Quebec to Laredo, Texas. With a fleet of 400 trucks, C.A.T. decided to operate the trucks on CNG but needed support from CNG refuelling infrastructure. The Mississauga CNG station is a good example of efficient infrastructure development. The combination of an anchor tenant Emterra having a return to base refuse truck fleet, together with the long haul C.A.T. trucks, satisfies both the station owners and the truck customers, guaranteeing the high station loadings necessary to ensure viability of the station.

A further Gain Clean Fuel CNG station was opened in November 2015 in Coteau-du-Lac, QC in partnership with C.A.T. and Gaz Metro. This is the second of five GAIN Clean Fuel station locations to open in partnership with C.A.T. [**44**]

FIGURE 3.34 shows graphically the limit of CNG refuelling along the Ontario Quebec freight corridor to specifically support Class 8 freight traffic. [**45**]

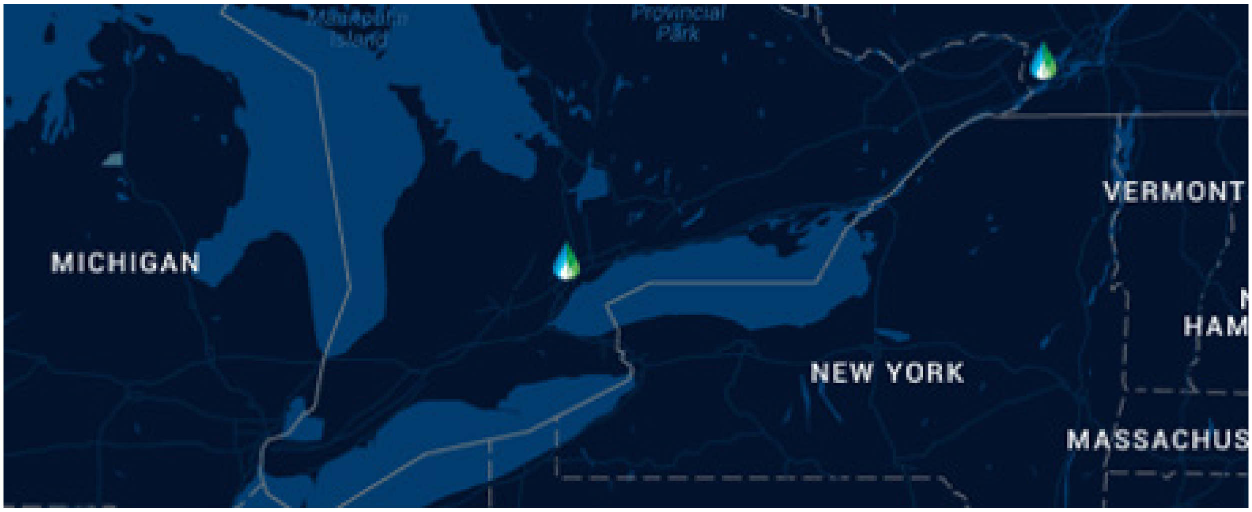


FIGURE 3.34 Ontario and Quebec – GAIN Clean Fuel - CNG Fuelling Stations

In December 2015, it was announced that Fiat Chrysler Automobiles recently invested in 179 Detroit-based parts-haulers for FCA Transport, fuelled by compressed natural gas. [47] The tandem axle day cab Peterbilt 579 tractors with the ISX12 G engine, Hexagon Lincoln CNG cylinders in back-of-cab Agility Fuel Systems assemblies holding 160 diesel gallon equivalents of natural gas. The range on this truck is about 1,030 km (640 mi). All the FCA Transport parts trucks operating out of the Detroit area are now CNG-fuelled. The company is considering CNG trucks for its terminals in Windsor, Ont. and Toledo, Ohio. Currently there are trucks crossing into Ontario traveling as far as the Brampton area. Detroit, MI trucks dispatched to Brampton, ON, travel approximately 352 km (219 mi) each way. FCA also has a truck fleet based in Windsor and company officials say they are looking at the performance of the Detroit fleet before possibly extending the CNG conversion to this side of the border. [48] Although FCA has not yet decided to convert its Canadian-domiciled trucks, it may represent a near term next step.

Given the availability of the 12L natural gas engine, the need for refuelling infrastructure to support an expanded fleet market to serve this major freight corridor is critical.

Canadian trucking industry trends emphasize a move towards a more regional haul model, incorporating the use of freight corridors and trucking hubs. Essentially, these include the Ontario-Quebec corridor, encompassing the Montreal to Peel, to Windsor, ON – Detroit, MI, to Niagara Falls, ON – Niagara Falls, NY. These routes become key determinates for NG station placements. Establishing this infrastructure based on carrier driving patterns, desired locations of stations and desired distance between stations is important.

The ability to address fuel consumption and associated loss of driving range during border crossing wait times was not studied but might influence carrier needs for specific refuelling “not far” from entry points into Ontario and Quebec.

Since there are many vehicle CNG tank packages available (involving range, cost and onboard additional weight trade-offs) and operating factors (nature of freight being carried, degree cubing out or weighing out, customer locations, overall logistics strategy, typical way points, etc.) that influence the minimum number of stations and the best suited locations. Near term gaps as to where to deploy stations appear to support a need around major warehouse and logistics centres in Ontario (example: Peel, Cornwall, London, etc.).

Natural Gas Refueling – ONTARIO Public Access CNG Stations

Station	City	Directions	Contact Information	Hours of Operation
ATW ◊ Automotive	Chatham	733 Park Avenue West	519-354-6978	Mon- Fri: 8-5 Closed Saturday and Sunday
Kiff Auto ◊	Peterborough	1031 Highway # 7 East	705-749-1805	Mon- Fri: 8-5
Kingsmill * Grain	Aylmer	47228 Ron McNeil Line	519-521-5101	Open 24 hrs
Pilot Flying J	Etobicoke	1765 Albion Rd & Hwy 27	416-674-8665	Mon-Sat: 5:30 – 10 Sun: 7:30 -10
Pioneer Snack Express	St. Catharines	383 Ontario Street	905-684-4955	Open 24 hrs

TABLE 3.1 Greater Toronto Area – CNG Fuelling Stations

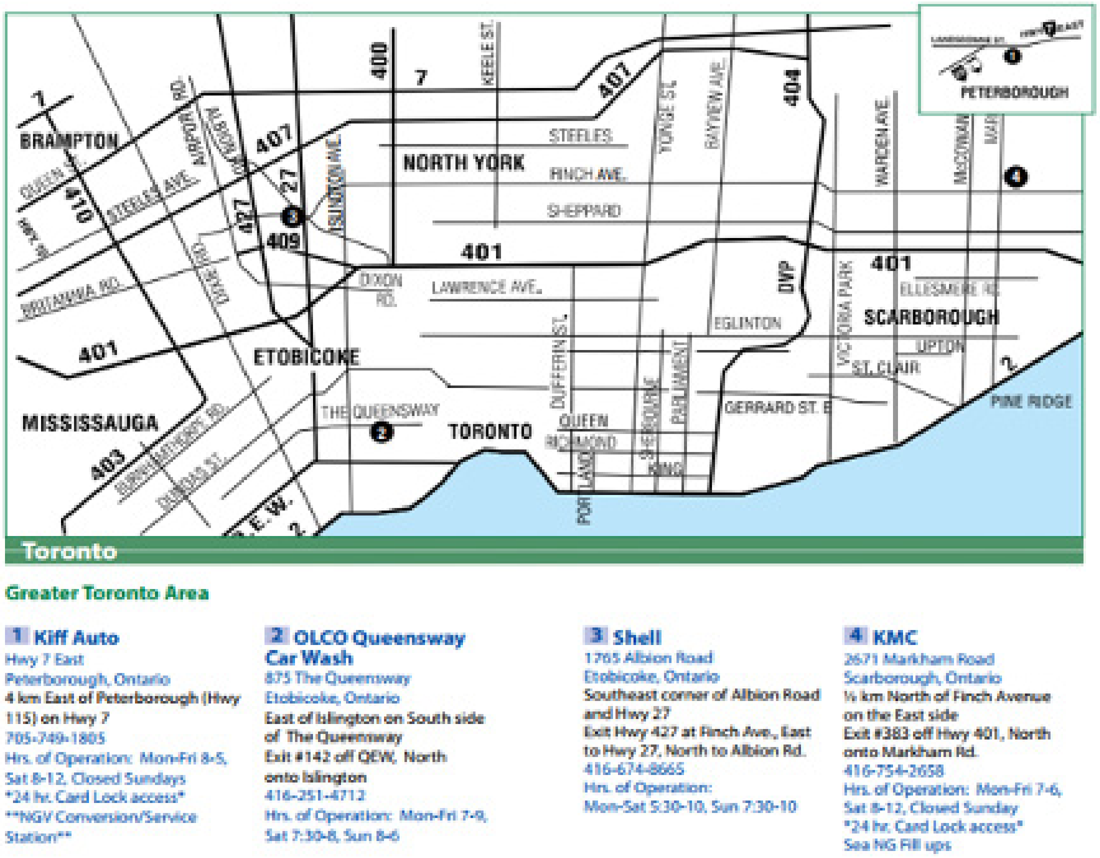


FIGURE 3.35 Toronto Area – CNG Fuelling Station Location Map

There are some existing CNG public refuelling stations in or near Toronto (and as distant as Peterborough and Chatham) as shown in **TABLE 3.1** [**49**] and **FIGURE 3.35**. [**50**] Upon review they do not appear to be ideally or strategically best located to best serve Class 8 freight traffic moving in and through the Toronto area. The writer did not assess the existing utilization and effectiveness of these CNG stations.

3.7.5 Considerations for Future CNG Stations – Ontario – Highway 401/QEW Focus

The following consideration for potentially siting CNG stations along the Ontario – Quebec Corridor is focused on identifying locations along Highway 401 and the QEW. Although consideration could be given to places along side Highway 402, 403 and the 407, the current outlook for growth and overall volume remains strongest along the 401 and QEW routes.

Given the current location truck ship from, ship to, way points, existing traditional service centres and current location of public accessibly CNG stations as well as a high-level understanding of vehicle range the following centres from which to plan a radially placed specific location should be considered.

The following key destinations, junctions or way points are highlighted as areas where significant volume of traffic exists today and is forecasted to grow and can form the basis where CNG refuelling could be strategically deployed based on the supporting data and information contained in this report as part of a long-range approach.

Primary location – near term deployment corridor and community (to grow HD freight movement using CNG)

- 401 - Windsor to Chatham - consider Windsor (east) or Chatham (west)
- 401 - London to Woodstock - consider community of London (east) or Woodstock (west)
- 401 - Kitchener-Waterloo to Guelph - consider community of Cambridge or Guelph
- 401 - Pickering to Newcastle - consider community of Oshawa (east) or Bowmanville
- 401 - Brockville to Cornwall - consider community of Cornwall
- QEW – St. Catharines to Fort Erie - consider community of St. Catharines (east) or Fort Erie (west)

A priority should be given along the western portion of highway 401 between London to Woodstock. The second priority should be given along the QEW highway between St. Catharines to Fort Erie.

Secondary – longer term corridor and community (as fleet utilization of CNG increases)

- Additional CNG refuelling – Milton, Mississauga and Toronto area
- 401 - Port Hope to Trenton - consider community of Port Hope or Trenton
- 401 - Belleville to Brockville - consider community of Kingston (east) or Gananoque (west)
- QEW – Burlington to Grimsby – consider community of Hamilton or Grimsby

Future considerations and study could focus on additional freight traffic like highway 402 (London to Sarnia), highway 403 (Woodstock to Hamilton) and highway 407 (currently no data available) and the potential impact of longer-term developments associated with the Ontario Proposed Growth Plan 2016 (Infrastructure to support growth - moving goods and infrastructure corridors) and the future outcome of Greater Toronto Area West Corridor Project (currently on hold).

General, macro, area and /or city location level information can only be highlighted in this brief study. It is beyond the scope of this report to provide micro planning, specific geography and/or exact real estate location levels to be considered.

An additional focused study with targeted potential fleet trucking associations, key freight carriers and other planning and data gathering could be considered to better refine detailed locations.

3.7.6 Natural Gas and Battery Electric Heavy-Duty Truck Trend

Several factors are continuing to support a shift to CNG. Carriers are changing to a hub and spoke configuration which reduces the range requirements for Class 8 trucks and results in more regional operations well suited to CNG infrastructure. The nodes in truck movements are ideally suited for placement of CNG stations. The 12L CWI engine operating on CNG with storage up to 1900 km (1200 mile) range can be achieved with sufficient CNG on-board storage that might provide an upper limit to storage with economics likely driving drive to storage to be less and to be specific to support fleet operations. Creating a reasonably visible network of CNG stations along major freight corridors will create awareness, support further adoption and provide sufficient comfort to carriers and their drivers operating tractors on natural gas.

3.8 Overall Freight and GVW Trends, U.S. Influence

This section presents a brief discussion of the U.S. truck market, overall freight information and trends in changing GVW, and its potential influence on the Canadian market is covered. This is based on information and data that does not consider the impacts of COVID-19.

3.8.1 Freight and GVW Trends

This study does not attempt to define the nature of freight expected to be transported in the future but the general effects and shifts to and from heavy manufactured goods (autos, machinery, equipment, etc.) and basic commodities (steel, wood products, aggregate, etc.) versus general consumer products or warehousing will influence the overall traffic volume, specific capable trucks of hauling specific freight and need for adequate refuelling, rest stops and other delivery factors.

As previously shown in this report, the Ontario Ministry of Transportation, the Transportation Border Working Group (TBWG) and additional studies by the McMaster Institute of Transportation and Logistics will likely continue to be great resources to track, study or potentially leverage for potential future specific studies.

The trends and needs will likely continue to evolve to support the Ontario and Quebec freight corridor requiring the flexibility to haul in and through the Quebec - Ontario corridor, to and from ports, rail and border points, traffic congestion and noise while serving the main population centres in southern Ontario and Quebec.

Ontario has defined specific requirements relative to the safe operation of Long Combination Vehicles on provincial highways. The details can be found at www.mto.gov.on.ca/english/trucks/long-combination-vehicles.shtml (Accessed, 26 April 2021)

The Long Combination Vehicle (LCV) Program supports the efficient movement of goods across the province and beyond. A typical LCV is up to 40 metres long, consisting of a tractor pulling two full-length semitrailers. A standard LCV replaces two 23-metre tractor-trailers.

MTO gradually introduced LCVs onto Ontario roadways by issuing a limited number of permits to a limited number of carriers. This has allowed for a carefully controlled and closely monitored program. LCVs have been on the road in Western Canada, Quebec, and numerous American states for decades.

See **APPENDIX A3.5** for some additional details defining eligible vehicles including weight and dimension restrictions.

3.8.2 Overall U.S. Influence

The influence of the U.S. cannot be understated as it relates to the HD Class 8 truck market. The product offerings will be heavily directed by U.S. based OEM's and their read of the needs of the Canadian fleets will impact CNG refuelling needs going forward. The macro influence of cross border trade and freight movement between the two jurisdictions will also impact the nature of regional haul, GVW of the commodities transported and again the nature of CNG refuelling needs. This will change based on industry and consumer demand to move specific goods.

To the extent U.S. carriers adopt CNG Class 8 vehicles into their fleet, the nature of the goods carried into Canada and the availability of sufficient natural gas infrastructure will also impact the Canadian regional haul routes especially in the Ontario and Quebec 401 - QEW corridors and to future opportunities along other Ontario highways. Any activity on the regulatory front that changes GVW and ESAL requirements at the Federal and State level may have ripple effects as it relates to Canadian, Provincial and Territorial harmonization initiatives and factors that fundamentally impact the movement of freight. The degree to which U.S. carriers are cubing out versus weighting out especially on CNG trucks might create a variation in actual GVW regulations at the jurisdictional level to support specific industry, freight movement needs. This same strategy might also come into play within Canada.

3.9 Codes, Standards and Regulations – Over the Road Focus

This report is focused on a brief overview of codes, standards, and regulations as it relates mostly to the on-road transportation sector. It relies heavily on material contained in three other primary Natural Resources Canada funded reports titled: *2019 Hydrogen Pathways – Enabling a Clean Growth Future for Canadians*[7], *Hydrogen and Fuel Cells Sector Status and Vehicle use in Canada" both published in April of 2019*[8] and *Environmental scan and gap analysis of codes and standards related to hydrogen in Canada* prepared in October 2019.[9]

3.9.1 Federal, Provincial and Territorial Regulatory Landscape

As is relates to the gas industry, there are three primary types of code documents: gas installation codes (CSA B149 series); boiler and pressure vessel codes (CSA B51 series); and oil and gas pipeline codes (CSA Z662 series). Specifically, for hydrogen, there also exists the Canadian Hydrogen Installation Code (CAN/BNQ 1784-000).

The third report referenced above provides much detail surrounding the Authorities Having Jurisdiction for Gas Codes and Oil and Gas Pipeline Codes. It includes tables that illustrates the gas installation codes, boiler and pressure vessel code, and the oil and gas pipeline code, and where they are drawn into regulation. The authorities having jurisdiction (AHJ) at a federal level and in each province and territory are identified for the Boiler and Pressure Vessel Code, Gas Installation Codes and the Oil and Gas Pipeline Code. At a federal level, these organizations are responsible for the approval and adoption of the industry code as a Canadian National Code. The provincial and territorial AHJs are responsible for the implementation of the regulations that draw these codes into regulation within their jurisdictions.

Similar to the Gas Installation Code for Natural Gas and Propane, the Interprovincial Gas Advisory Council (IGAC) approves the Canadian Hydrogen Installation Code (CHIC), and its adoption as a national standard. The code is currently drawn into regulation in New Brunswick, Newfoundland and Labrador, Ontario, Prince Edward Island and Saskatchewan. Additionally, Alberta, British Columbia, and Quebec are currently following the code for hydrogen installation approvals and are in the process of adopting the code into their regulations.

The provincial and territorial AHJs for the Boiler and Pressure Vessel Code and the Gas Installation Code are the same in each jurisdiction, and all jurisdictions draw these codes into regulations, in part or in whole.

7 https://www.nrcan.gc.ca/energy/transportation/alternative-fuels/resources/21961 (Accessed, 26 April 2021).

8 https://www.nrcan.gc.ca/energy/transportation/alternative-fuels/resources/21959 (Accessed, 26 April 2021).

9 Report prepared by KauliNG Solutions for Natural Resources Canada

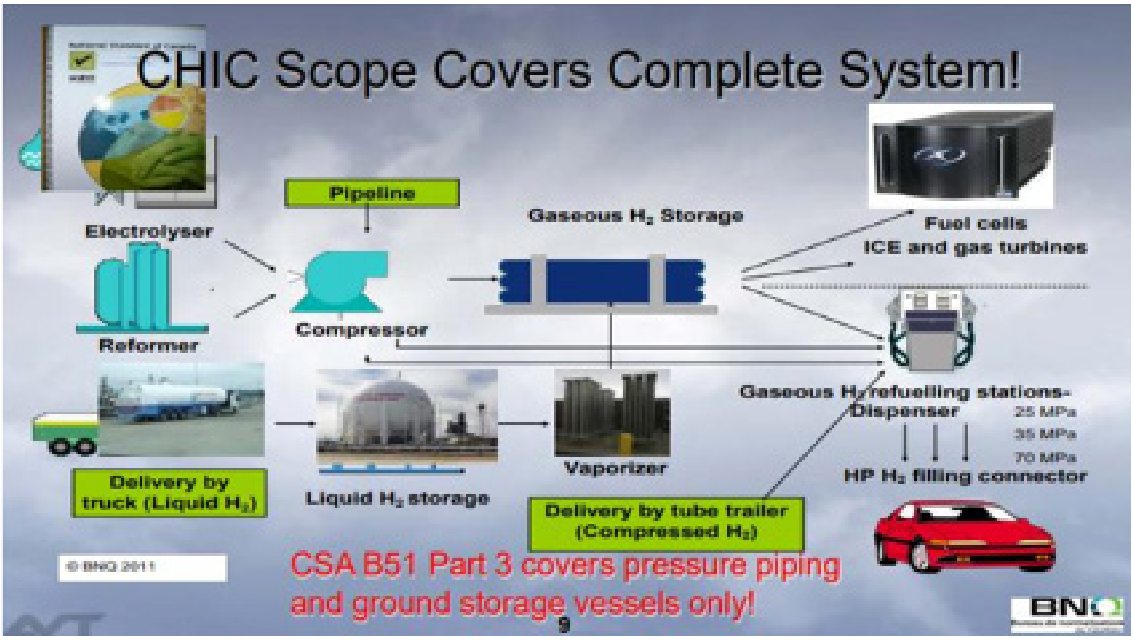


FIGURE 3.36 Canadian Hydrogen Installation Code Illustration of Document Scope

3.9.2 Focus on the Canadian Hydrogen Installation Code (CAN/BNQ 1784-000)

As previously identified, the primary hydrogen focused code document, being adopted across Canada, is the CHIC (CAN/BNQ 1784-000).

The purpose of this code is to establish the installation requirements for hydrogen generating equipment for non-process end use, hydrogen utilization equipment, hydrogen dispensing equipment, hydrogen storage containers, hydrogen piping systems and their related accessories. The scope of this document provides a complete system solution as shown in **FIGURE 3.36**.[10]

The focus of the code is the use of hydrogen as a fuel. It applies to all gaseous and liquid hydrogen applications except the following:

a) the use of hydrogen in petroleum refineries and chemical plants as feedstock and directly in-process production;
b) industrial installations that produce hydrogen as a by-product that is vented to atmosphere;
c) cryogenic systems used for hydrogen liquefaction;
d) hydrogen installations onboard vehicles (e.g. rail, boats, airplanes and space vehicles) for onboard use;
e) vehicles that use hydrogen for propulsion;
f) hydrogen transportation including the hydrogen utility pipeline distribution and transmission pipelines;
g) industrial facilities, at which hydrogen is generated, handled and stored for off-site end-use.

10 ISO-IPHE RCSS Strategic Planning Meeting (December 5, 2018 Vancouver) - Andrei V. Tchouvelev, Chair, BNQ CHIC Technical Committee http://www.hydrogenandfuelcellsafety.info/january-2019#Update2. (Accessed, 26 April 2021).

Some of the above exceptions are currently addressed in other code and standards documents not covered in this report. Transportation – On Road Sector Standards

The on road transportation sector has several on-road light duty hydrogen fuel cell vehicle related standards that are relatively new (compared to standards in other sectors in the Canadian economy) but are actively being developed by CSA Group, SAE and ISO, which are the dominant forces involved in coordinating, developing and maintaining harmonization of technical requirements. This is in support of efforts at the United Nations - Economic Council for Europe (UN-ECE) to establish Global Technical Regulations (GTRs).

With accreditation from the SCC and the American National Standards Institute (ANSI), CSA Group (CSA) has a long history of developing alternative energy standards applying to alternative energy products. CSA developed the first fuel cell standard in 1998. Working with the automotive industry and other stakeholders, CSA facilitated the development of the standards that are used today for hydrogen dispensing, storage, and infrastructure as well as for other fuel cell applications as shown in the illustration in **FIGURE 3.37**.[11]

All of CSA's hydrogen refuelling and vehicle-related standards have been updated within the past five years. CSA also has certification and testing services available at its Langley, B.C. location for certifying high pressure hydrogen components for global markets, and for conducting fuel cell power certifications.

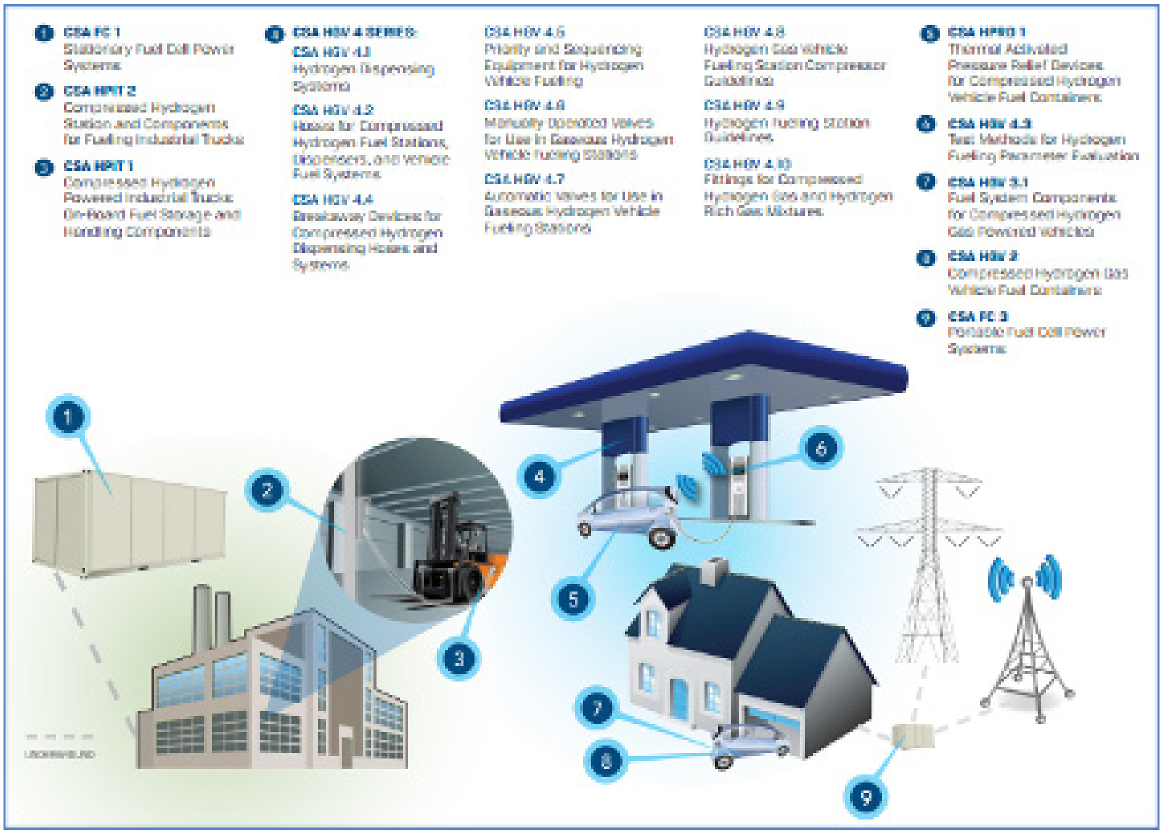


FIGURE 3.37 CSA Illustration: "Hydrogen technologies are driving our future..." (February 2018)
SOURCE: CSA GROUP

11 Copy obtained by D.C. Kauling from CSA Group (Brent Hartman) – public marketing material (as of February 2018)

CSA GROUP	BNQ
• Standardization for fuel cells, hydrogen refuelling infrastructure, and vehicle components in the USA. • Canadian and U.S. adoption rights for ISO standards published by the ISO Technical Committee (TC) 197 Hydrogen Technologies that are derivative works of CSA seed documents covered by a Copyright License Agreement between CSA and ISO. These are defined as standards that ISO publishes that are the same or address similar content to existing CSA standards.	• International standards development for hydrogen technologies. • Canadian adoption rights for ISO standards published by ISO TC 197 that are not derivative works of CSA seed documents.

TABLE 3.2 Roles and responsibilities of CSA Group and BNQ per the MOU

CSA signed a memorandum of understanding (MOU) with the BNQ in 2016[12] which defines reasonable efforts to carry out specific activities and recognizes each organization's role, as shown in **TABLE 3.2**. The purpose of this MOU was to support and foster collaboration efforts in codes and standards for hydrogen and fuel cell technology in Canada. The agreement does not limit either party's right to work with other SDOs or independently. It was also stated that both parties would use their reasonable efforts to carry out the following activities or tasks.

In addition, the MOU states that both parties agree to develop Canada-USA harmonized adoptions wherever possible, and where appropriate for hydrogen technology standards. The agreement also notes that the CHIC should give preference to Canadian adoption of international standards. In the absence of international standards, reference should be to North American standards.

Where additional standards for hydrogen technologies are requested by North American industry stakeholders, CSA and BNQ have also agreed to evaluate the possibility of collaboration in the development of additional standards. As desired by ISO/TC197, these published standards may be submitted as seed documents for international standardization. Both organizations will advise of technical issues and keep each other updated on their respective standardization activities.

Many of these CSA standards could be considered, in whole or in part, as Canada reviews and engages in the ongoing development of the CHIC or considers additional requirements or alternatives. The feasibility of this strategy has not been fully assessed as part of this study, but it presents a compelling consideration.

The good news is that this foundational work, which was done across international boundaries and through the strong support of government, industry and SDOs, has resulted in a common framework and approach to the development of the refuelling interface, fuelling protocols, and certification of hydrogen dispensing stations.

Conversations with the SDOs indicate that there are efforts to add specific requirements for medium and heavy-duty applications (transit buses and heavy-duty trucks). Details can be found when researching Hydrogen and Fuel Cell Vehicles Global Technical Regulation No. 13 (Phase 2).

12 Source: Correspondence between D.C. Kauling and CSA on 03-17-2017– Copy of Memorandum of Understanding (MOU) between BNQ and CSA

Authorization to develop Phase 2 of GTR No. 13 (Hydrogen and fuel cell vehicles) was submitted by the representatives of the European Union, Japan and Republic of Korea back in 2016 with details surrounding the background, proposal and timing back in December of 2016. [13]

As a result of that action, a "Hydrogen and Fuel Cell Vehicles Global Technical Regulation No. 13 (Phase 2) Informal Working Group (GTR13)[14] was established to further develop GTR No. 13, including consideration of the following:

- harmonization of crash test specifications,
- revision of the scope to address additional vehicle categories,
- refinement of test procedures and correction of errors,
- material compatibility and hydrogen embrittlement,
- evaluation of performance test and stress rupture proposed in Phase 1,
- electric barrier enclosure, and
- consideration of research results reported after completion of Phase 1.

The group has also established five task forces on:

- heavy duty vehicles and buses,
- fuelling receptacle requirements,
- recommendations for test procedures,
- fire test, and
- recommendations from standardizations organizations.

For more information readers are encouraged to go to the United Nations Economic Commission for Europe where they have a visible dashboard on vehicle regulations and the working party on Passive Safety (GRSP) focused on Hydrogen and Fuel Cell Vehicles (HFCV). There one will find posted information outlining activities associated with seven sessions held to date in support of GTR 13 Phase 2. [15]

There is no real evidence of any code or standard development activity focused on any over the road or off-road hydrogen applications for spark ignited or compression ignition powertrains. Certainly, aspects of component selection could be derived from selected hydrogen fuel cell standards. Emerging interest and applications associated with off-road mining vehicles could also benefit from selected hydrogen fuel cell standards. The impact on engine performance, control, emissions, fuel consumption and durability would need to be addressed separately.

For a more comprehensive assessment of the on-road transportation sector, readers of this report may wish to explore the *Hydrogen and Fuel Cells Sector Status and Vehicle use in Canada* report, which was commissioned by Natural Resources Canada and published in April of 2019.[16]

13 https://www.unece.org/fileadmin/DAM/trans/doc/2016/wp29grsp/GRSP-60-24e.pdf

14 https://globalautoregs.com/about_group?id=110

15 https://wiki.unece.org/pages/viewpage.action?pageId=3178603

16 https://www.nrcan.gc.ca/energy/transportation/alternative-fuels/resources/21959

Light Duty Vehicles

For a more comprehensive assessment surrounding the over the road transportation sector, readers of this report may wish to explore in more detail chapter 13 Safety, Codes, Standards, and Regulatory Readiness in another primary Natural Resources Canada funded report stated earlier titled: *Hydrogen and Fuel Cells Sector Status and Vehicle use in Canada" published in April of 2019.*[17]

The above referenced report provides a transportation focus on safety, codes, standards, and a regulatory readiness assessment by going into more detail surrounding the following topics:

- Codes, Standards and Regulatory Framework
- Canadian Hydrogen Installation Code
- International Standards
- USA Codes and Standards
- CSA Group Codes, Standards, Testing, and Certification Services
- SAE Automotive Standards
- Compressed Gas Association Standards
- Regulations and Harmonization
- Natural Resources Canada – U.S. Department of Energy Regulatory Cooperation
- Transport Canada and U.S. National Highway Traffic Safety Administration
- Global Technical Regulation
- Measurement Canada – Metrology Regulations
- Other Relevant Codes, Standards and Regulatory Activity
- CSA Group – Hydrogen Codes and Standards Forums

Another good source of information indicating the direction of hydrogen transportation-based activities in the United States is through U.S. DRIVE (Driving Research for Vehicle efficiency and Energy sustainability), which is a voluntary government industry partnership focused on pre-competitive, advanced automotive and related infrastructure technology research and development. Partners are the U.S. Department of Energy (DOE) and leaders in the automotive industry (US Council for Automotive Research LLC, the collaborative technology company of FCA US LLC, Ford Motor Company, and General Motors); energy industry (BP, Chevron, Phillips 66, ExxonMobil, and Shell); and electric utility industry (DTE Energy, Southern California Edison, and the Electric Power Research Institute).

17 https://www.nrcan.gc.ca/energy/transportation/alternative-fuels/resources/21959. (Accessed, 26 April 2021).

FIGURE 3.38 U.S. Drive Technical Team Roadmap Reports.

In 2017, US DRIVE published three key documents focused on hydrogen: Hydrogen Delivery,[18] Codes and Standards[19] and Hydrogen Production[20] Tech Team Roadmap Reports as shown in **FIGURE 3.38**. These references provide visible evidence of a focused technical activity in support of the U.S. hydrogen and fuel cell industry. These three documents were not assessed in detail for this report to evaluate any specific impacts to Canadian codes and standards. As part of this overall activity, US DRIVE reported on some specific hydrogen activities accomplished in 2018 on several fronts. [21]

The August 2017 publication Hydrogen Code and Standards Technical Team Roadmap, offers a then current state of regulations, codes and standards (focused on National Fire Protection Association (NFPA) 2 Hydrogen Technologies Code 2016 and Continuing Revisions; the Global Technical Regulation (GTR) for hydrogen vehicle systems; SAE J2579, hydrogen fuel quality specification SAE J2719 and ISO 14687-2; modification of American Society of Mechanical Engineers (ASME) qualification test procedure for hydrogen service; and the generation of fork truck product safety standards. It also addresses the Gaps and Barriers to Reach Technical Targets (including a codes and standards gap analysis and factors that affect the widespread deployment and commercial scale-up issues for a hydrogen infrastructure).

Specifically, as part of the overall codes and standards technical team roadmap, there was a recognized need for new standards to be developed to address hydrogen compatibility of polymeric materials in infrastructure. In this case, national laboratories and industry partnered to develop new standards and test methodologies that will help to improve polymer material durability and reliability for the hydrogen industry. Pacific Northwest National Laboratory (PNNL), Sandia National Laboratories, Oak Ridge National Laboratory, and Ford teamed

18 https://www.energy.gov/sites/prod/files/2017/08/f36/hdtt_roadmap_July2017.pdf. (Accessed, 26 April 2021).

19 https://www.energy.gov/sites/prod/files/2017/09/f36/2017%20CSTT%20Roadmap_FINAL.pdf. (Accessed, 26 April 2021).

20 https://www.energy.gov/sites/prod/files/2017/11/f46/HPTT%20Roadmap%20FY17%20Final_Nov%202017.pdf. (Accessed, 26 April 2021).

21 https://www.energy.gov/sites/prod/files/2019/04/f61/2018_U.S._DRIVE_Annual_Accomplishments_Report.pdf. (Accessed, 26 April 2021).

to close knowledge gaps and support hydrogen (H_2) stakeholders in the proper selection of polymers for H_2 applications. This work resulted in the new ANSI/CSA CHMC 2-2018 standard "Test methods for evaluating material compatibility in compressed hydrogen applications—Polymers".

Another 2018 activity being reported on is a project to support wireless, high-accuracy hydrogen dispensers using emerging secure wireless vehicle-dispenser communication methods and novel Coriolis meters to enhance the reliability and accuracy of hydrogen fuelling. In 2019, this project includes building the dispenser prototype and validating its performance at the National Renewable Energy Laboratory's Hydrogen Infrastructure Testing and Research Facility.

Another project has efforts focused on an electrochemical hydrogen compressor reporting record-setting electrochemical hydrogen compression efficiency for 350-bar operation. In 2019, the focus is on enhancing the durability of the system components.

Also, worth stating is some focused research on a platinum-free catalyst that outperforms platinum for microbial electrolysis hydrogen production. Using a molybdenum-phosphorous catalyst resulted in a higher activity and durability than platinum catalysts and a 5x improvement over platinum-free catalysts reported in the literature for microbial electrolysis.

The automotive / transportation space continues to drive and advance the technology that will directly or indirectly continue to impact codes and standards going forward.

Medium / Heavy Duty Vehicles

In interviews with various SDOs, it was identified that there are ongoing efforts to expand and advance standards that were originally developed for the light duty market. These stands will support hydrogen-fuelled fuel cell powered medium and heavy-duty applications (transit buses and heavy-duty trucks). Much can be drawn from the materials and discussion associated with the reference material stated in the light duty vehicle section above.

The U.S. DRIVE Advanced Combustion and Emission Control (ACEC) Tech Team published an Advanced Combustion and Emission Control Roadmap in March 2018 that included a three-page discussion on the current state of the art of hydrogen internal-combustion engine technology. It provided a current state of hydrogen ICE technology and the remaining research barriers. It outlines the technology development history, specific barriers and associated technical strategies focused on combustion technologies and after-treatment technologies that need to be addressed in support of specific hydrogen engines. Based on research and funding priorities, research on hydrogen-fuelled ICEs has been tabled at this time. [22]

As in light duty vehicles, there is currently, no real evidence of any code or standard activity focused on any on- road or off-road hydrogen applications based on spark ignited or compression ignition powertrains. Certainly, aspects of component selection could be derived from selected hydrogen fuel cell standards. Emerging interest and applications associated with off-road mining vehicles could also benefit from selected hydrogen fuel cell standards. The impact on engine performance, controls, emissions and durability would need to be addressed separately.

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22 https://www.energy.gov/sites/prod/files/2018/03/f49/ACEC_TT_Roadmap_2018.pdf. (Accessed, 26 April 2021).

3.10 Conclusions — HD Transportation Related-Draft

Major freight routes in Canada include the relatively flat and limited grade highways of southern Quebec and southern Ontario along the 401 - QEW corridor with significant links and cross border traffic into the northeast United States.

The currently available Cummins-Westport 400 HP 12L NG HDV along with a variety of on-board vehicle CNG storage options meets the basic need to move freight up to 36,300 kg GVW (80,000 lb GVW).

The CNG trucks operated by C.A.T using natural gas and operating along the Quebec, Ontario corridor and down into the U.S. and FCA Transport from Michigan to Brampton were not fully assessed in this study due to the recent in process deployment of these vehicles. Assessments as it relates to CNG refuelling have not been made and may need to wait until C.A.T. and FCA Transport begins to share its experiences and lessons learned. Evidence of similar trucks operating and performing well in the US, does suggest the potential for additional U.S. and Canadian carriers to expand the use of natural gas as a transportation fuel and could also offer insights to the use of hydrogen powered vehicles and supporting infrastructure.

Market available natural gas trucks are capable of significant penetration into this market given the right supporting conditions exist. One of the primary conditions is a sufficiently deployed and appropriately sized CNG refuelling infrastructure to support early adopters around strategic freight hubs and way points.

Lack of hydrogen refuelling stations in eastern Canada will obviously significantly limit the suitability of hydrogen-fuelled vehicles in transporting freight.

Voice of the client / customer in need of freight services, vehicle and engine OEMs, carriers, owners, owner/ operator, drivers, leasing companies, first time vehicle buyer and secondary market buyer for hydrogen HDV are all closely interdependent. The entire value stream must see their respective value proposition for the entire lifecycle of the CNG of hydrogen-fuelled vehicle and supporting CNG or hydrogen refuelling infrastructure to achieve sustainability.

The life cycle costs of hydrogen refuelling stations is highly dependent on the number of vehicles creating sufficient demand load based on critically deployed locations. These locations can best be determined on a careful and detailed understanding of the nature of freight moment and targeted fleets that pass through or are centrally based with easy, safe, and reliable access.

The focus of this report was on the Ontario-Quebec corridor regional haul Class 8 heavy-duty truck segment of the market but the size and influence of the existing Class 7 medium duty truck market will also influence the growth of natural gas, hydrogen and electric vehicles and its associated fuelling or charging infrastructure.

Ministry of Transportation of Ontario future planning, forecasting information along with the assessments based on future Commercial Vehicle Survey results along with Equivalent Single Axle Loading information should be studied more going forward to continue to address changes in the nature of freight movement through the Ontario – Quebec corridor and guide future hydrogen vehicle designs and hydrogen refuelling technology and locations.

McMaster Institute of Transportation and Logistics research can be studied in much more detail in order to gain additional insights as to specific movement of Class 8 trucks by looking closely at start and end destinations, way points, rest locations and where these vehicles tend to prefer to refuel.

Additional information from the Canadian or Ontario Trucking associations, their associated members and others freight carriers was not considered for explored in support of this brief study.

Currently there is insufficient CNG refuelling stations along the Ontario-Quebec corridor to support the future growth of CNG Class 8 vehicles. Beyond the two CNG stations identified (Milton, ON and Coteau-du-Lac, QC), there is a clear lack of refuelling at primary geographic junctions along selected sections of the King's Highways.

Significant existing and forecasted growth of truck traffic, as illustrated with the data presented, along several segments of the Ontario-Quebec freight corridor is presented with an emphasis along the western portion of highway 401 between London to Woodstock and along the QEW highway between St. Catharines to Fort Erie.

Future considerations and study could focus on additional primary and secondary locations highlighted in this study along with a longer view on additional freight highways and impact of Ontario's Proposed Growth Plan.

3.11 Recommendations — HD Transportation Related-Draft

In order to be well positioned for future opportunities a detailed focused study and ongoing monitoring as it relates to U.S. federal and state activity as it relates to natural gas and hydrogen HDV offerings, applications and general changes in the movement of freight into Canada that might impact the movement of goods and demand for additional hydrogen powered vehicles and hydrogen refuelling needs should be considered.

Additional detailed studies or research should be considered to best identify likely key heavy-duty fleets currently operating on CNG, considering electric and/or considering hydrogen in the U.S. that might consider traveling into Ontario and Quebec to best situate hydrogen refuelling to support their direct needs and create an understanding of base load on future hydrogen station(s).

Canadian freight carriers considering the use of hydrogen in their operations need to be assessed to best understand their needs based on freight, destinations, specific routes, rest stops and refuelling needs to address economic considerations and avoid "range anxiety" as it relates to hydrogen refuelling.

Near term capital investments for hydrogen stations, based on a business case analysis, should only be considered if there is a clear view of targeted first adopter and early movers in the heavy duty truck fleet customer market that provides enough evidence of base load and future needs along the entire corridor.

Continue to monitor future CNG and EV infrastructure considerations and deployments based in the additional primary and secondary locations highlighted in this study along and provide insights for where to further consider hydrogen refuelling.

A continued review or active study based on Ministry of Transportation Commercial Vehicle Survey data and reporting, ongoing research conducted by the McMaster Institute of Transportation and Logistics and activities surrounding Ontario's Proposed Growth Plan would assist in ensuring a long term sustainable outlook for future hydrogen vehicles and infrastructure investments.

A separate effort to assess the impact of HD transportation post COVID-19 should be considered as the nature of freight is certainly undergoing some near-term changes that may indicate what future trends might look like. The nature of goods being transported along this corridor should clearly guide the design and deployment of hydrogen powered vehicles and supporting hydrogen fuelling infrastructure.

3.12 Conclusions — Codes, Standards and Regulations Related–Draft

Canadian Hydrogen Installation Code

The primary national hydrogen code, the Canadian Hydrogen Installation Code: CAN/BNQ 1784-000 (1st edition published in 2007), has been adopted by some but not all jurisdictions and a new edition is targeted for publication in November 2020.

The next edition will add many revised CSA standards to the requirements and references, with an increased focus on harmonization with CSA and ISO standards, as well as aspects of the USA NFPA 2 code document.

Opportunity exists for all existing Canadian hydrogen and fuel cell industry stakeholders, plus other industrial sectors looking at hydrogen applications in the future, to add value to the code document, through active participation in the technical committee or by providing input when it becomes available for public comments before final publication.

Continued activities to support ongoing harmonization of the document in the future, based on learning from Canadian project deployments as well as activities within other jurisdictions, is seen as beneficial and necessary to maintain harmonization of as many performance-based requirements as possible.

Once CHIC is published the adoption of the code, in its entirety or with changes as identified specifically, by Ontario, Quebec and the eastern provinces was not explored.

3.13 Recommendations — Codes, Standards and Regulations Related–Draft

Canadian Hydrogen Installation Code

Federal government should continue to support and drive Canadian jurisdictions to apply the next edition of the CHIC when it becomes available in 2020 and in direct support of any planned hydrogen technology deployment projects.

Government funded initiatives (regardless of level of government) should add specific program requirements to identify lessons learned and define any opportunities to address future codes and standards based on deployment experiences.

All levels of government and all industry stakeholders should continue to monitor codes, standards and deployment initiatives in other jurisdictions to stay current, maintain harmonization, and gain insights and lessons learned across existing codes and standards.

Appendix A3 Truck Terminology, Regulations and Classifications – Gross Vehicle Weight Focus

A3.1 Gross Vehicle Weight Classes and Categories

Canada has essentially adopted the same Gross Vehicle Weight Rating (GVWR) and Vehicle Use Service Categories as the U.S. Some references to the U.S. information is shared in this report to help better understand harmonization initiatives.

Gross Vehicle Weight Rating (lbs)	Federal Highway Administration		US Census Bureau
	Vehicle Class	GVWR Catagory	VIUS Classes
<6,000	Class 1: <6,000 lbs	Light Duty <10,000 lbs	Light Duty <10,000 lbs
10,000	Class 2: 6,001–10,000lbs		
14,000	Class 3: 10,001–14,000 lbs	Medium Duty 10,001–26,000 lbs	Medium Duty 10,001–19,500 lbs
16,000	Class 4: 14,001–16,000 lbs		
19,500	Class 5: 16,001–19,500 lbs		
26,000	Class 6: 19,501–26,000 lbs		Light Heavy Duty: 19,001–26,000 lbs
33,000	Class 7: 26,001–33,000 lbs	Heavy Duty >26,001 lbs	Heavy Duty >26,001 lbs
>33,000	Class 8: >33,001 lbs		

TABLE A3.1 Vehicle Weight Classes & Categories

TABLE A3.1 illustrates the vehicle weight classes and categories used by the U.S. Federal Highway Administration (FHWA), the U.S. Census Bureau, and the U.S. Environmental Protection Agency (EPA). [**51**]

The vehicle weight classes are defined by FHWA and are used consistently throughout the industry. These classes, 1-8, are based on gross vehicle weight rating (GVWR), the maximum weight of the vehicle, as specified by the manufacturer. GVWR includes total vehicle weight plus fluids, passengers, and cargo. FHWA categorizes vehicles as Light Duty (Class 1-2), Medium Duty (Class 3-6), and Heavy Duty (Class 7-8). Further detailed explanation of these categories is included in **SECTION A.3** of this appendix.

These categories are used by the trucking industry and many other government agencies to classify trucks. **FIGURE A3.1** shows examples of some of the different types of trucks that would be included in each class. [**52**] As an example, Class 8 describes a cement truck, truck tractor, dump truck and sleeper truck. A Class 7 vehicle could include a truck tractor.

In summary, this report will touch on some Class 7 (26,000 lb to 33,000 lb GVWR) truck tractors and mostly Class 8 (>33,000 lb GVWR) truck tractors. **FIGURE A3.2** illustrates the Canadian designation for Category 1 Tractor Semitrailer, and highlights the four and five axle configurations that is the primary focus of this report.

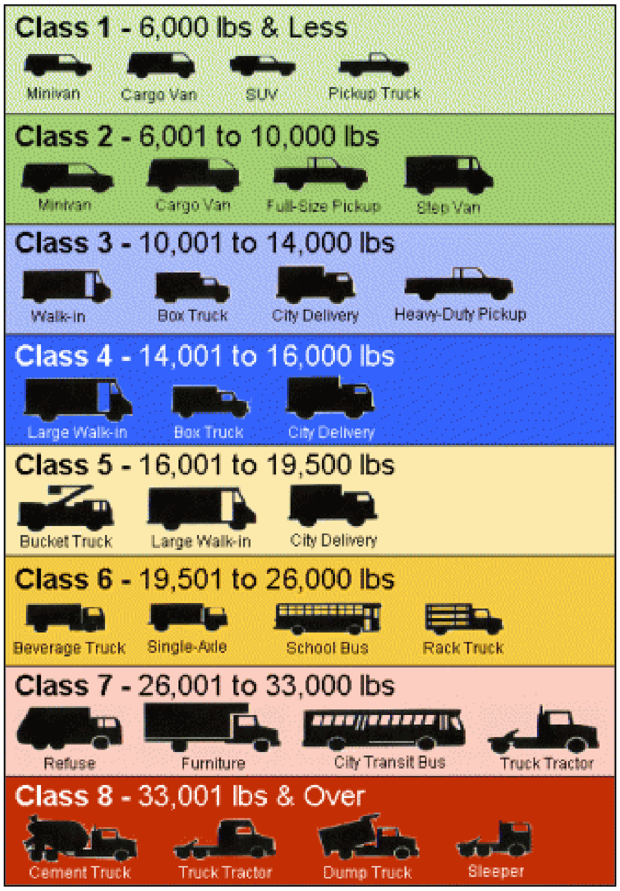
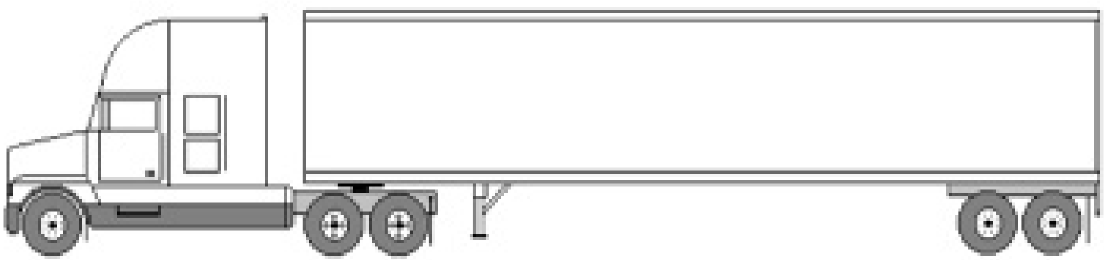


FIGURE A3.1 Illustration of Truck Classes



Gross Vehicle Weight Limits[2]		
Three Axles		Maximum 23 700 kg
Four Axles		Maximum 31 600 kg
Five Axles		Maximum 39 500 kg
Six Axles -	with 2.4 to < 3.0 m spread tridem	Maximum 43 500 kg
	with 3.0 m to < 3.6 m spread tridem	Maximum 45 500 kg
	with 3.6 to 3.7 m spread tridem	Maximum 46 500 kg

FIGURE A3.2 Category 1: Tractor Semitrailer

A3.2 Truck, tractor, trailer, long haul, short haul, regional haul, line-haul

"The terms trucks, tractors, trailers, and semis are often used improperly due to the combination of technical and layman use of each of these terms. The term "truck" technically refers to a vehicle designed for carrying the entire weight and bulk of a load. For single-unit heavy-duty vehicles, the entire vehicle is invariably referred to as a truck. However, heavy-duty vehicles with multiple units (often referred to as combination vehicles) are technically not trucks. These are tractors with one or more trailers, even though they are commonly referred to as trucks or semis.

A tractor is defined as a vehicle designed for pulling loads greater than the weight applied to the vehicle. The trailer on which the load is carried is generally connected to the tractor using a fifth wheel. To avoid confusion between the technical and common terms for trucks, tractors, and semis, the term heavy-duty vehicles (HDVs) is often used in technical fields to include non-light-duty trucks, tractors, and tractor trailer combination vehicles.

However, due to the common usage of the word truck in general items related to this research (i.e. truck company, truck size and weight limits, truck drivers, etc.), the term truck is often used interchangeably with heavy-duty vehicle in this report. Further discussion of the categories and classifications of tractors and trucks may be found in the report "Heavy-Duty Vehicle Weight and Horsepower Distributions: Measurement of Class-Specific Temporal and Spatial Variability." [**53**]

As discussed in **SECTION 1.1** of this report, the definition of the various terminology to describe the nature of the travel by length is variable based on common usage, but more importantly by local rules and regulations.

One example of the regulatory definition of "short haul" and "long haul" is found in the Province of British Columbia regulations:

- "**short haul truck driver**" means a person employed to drive a truck, usually for a distance within a 160 km radius of their home terminal; [**54**]
- "**long haul truck driver**" means a person employed to drive a truck usually for a distance exceeding a 160 km radius from their home terminal; [**55**]

Examples of the changing nature of the trucking industry and the length of travel are to be found in the articles "The End of Long Haul" [**56**] and "Regional Trucks Have Room to Optimize and Specialize." [**57**]

A3.3 Canadian National Standards for Heavy Vehicle Weights and Dimensions

As discussed in **SECTION 1.2**, the Canadian National standards for the weight and dimension limits of heavy vehicles used in interprovincial transportation are contained in a Federal/Provincial/Territorial Memorandum of Understanding (MOU).

TABLE A3.2 and TABLE A3.3 show the Gross Vehicle Weight (GVW) and Axle Load limits. Tables represent the values across Canada based on the MOU, and across each province and territory. It also highlights where there are some regional agreements and alignments based on the type of commercial vehicle.

This table was based on information contained in the August 2015 edition of Fleet Executive (Canadian magazine) hardcopy edition which also contained a copy of its annual poster sized Sizes and Weights Chart. [59]

The weights shown in these two tables is for information purposes only. Where differences exist between these tables and governing regulations, the regulations apply. The description of the various vehicles is based on the categories defined per the "Heavy Truck Weight and Dimensional Limits for Interprovincial Operations in Canada." [60]

Gross Vehicle Weights (by kg)	MOU	YK	NT	BC	AB	SK	MB	ON	QC	NB	NS	PEI	NL
Truck - 3 axles	24250	28200	24300	26100	24300	24300	24300	28100	25250	26000	26000	26000	26000
Tractor-semitrailer (3 axles)	23700	26000		24200	24200	24200		27700	25500				
Tractor-semitrailer (4 axles)	31600	35100		32100	32100	32100		36800	33500	32600	32600	32600	32600
Tractor-semitrailer (5 axles)	39500	44200		40000	40000	40000		45900	41500	41500	41500	41500	41500
Tractor-semitrailer (6 axles)	46500	49100		47000	47000	47000		52800	49500	49500	49500	49500	49500
A Train (5 axles)	41900	45500		42400	42400	42400	42400		45500				
A Train (6 axles)	49800	53500		50300	50300	50300	50300		53500	50800	50800	50800	50800
A Train (7 axles)	53500												
A Train (8 axles)	53500												
B Train (6 axles)	48600	54200		49100	49100	49100	49100	55900	53000	50600	50600	50600	50600
B Train (7 axles)	56500	63500		57000	57000	57000	57000	60500	59000	59500	59500	59500	59500
B Train (8 axles)	62500	63500	63500	63500	63500		63500	63500					
C Train (5 axles)	41900	45500		42400	42400	42400	42400		45500				
C Train (6 axles)	49800	54600		50500	50500	50500			53500	50800	50800	50800	50800
C Train (7 axles)	54600	60500		58200	58200	58200	53500		55900	55600	55600	55600	55600
C Train (8 axles)	58500	60500		60500	60500	60500	60500						
Truck and Pony trailer (6 axles)	45250	52200	48300	47100	45300	45300	45300	54100	49500	47000	47000	47000	47000
Truck and Full trailer (5 axles)	41250	47300	41300	43100	42500	41300	41300	46300	43500	43000	43000	43000	43000
Truck and Full trailer (7 axles)	55500	59200		57100	55500		55500	63000	55500				

MOU adopted   Regional Agreements / Alignments

TABLE A3.2 2015 Canadian Summary Gross Vehicle Weight Limits by KG

Axle Loads (by kg)	MOU	YK	NT	BC	AB	SK	MB	ON	QC	NB	NS	PEI	NL
Steering Axle - Tractors	5500			6000	6000	6000	6000	7700					
Steering Axle - Trucks	7250	7300	7300	9100	7300	7300	7300	9000		8000	8000	8000	8000
Single Axle - Dual Tires	9100	10000						10000	10000				
Tandem (1.2m spread)	17000	17900						18000	18000	18000	18000	18000	18000
Tandem (1.8m spread)	17000	19100						19100	18000	18000	18000	18000	18000
Tridem (2.4m spread)	21000	24000		24000				21500					
Tridem (3.0m spread)	23000	24000	24000	24000	24000	24000		24000	24000	24000	24000	24000	26000
Tridem (3.7m spread)	24000							26000	26000	26000	26000	26000	26000

MOU adopted   Regional Agreements / Alignments

TABLE A3.3 2015 Canadian Summary Axel Load Limits by KG

Jurisdiction	Website
British Columbia	http://www.th.gov.bc.ca/cvse/
Alberta	http://www.transportation.alberta.ca/3.htm
Saskatchewan	https://www.saskatchewan.ca/business/transportation-and-road-construction/information-for-truckers-and-commercial-trucking-companies
Manitoba	http://www.gov.mb.ca/mit/mcd/mce/index.html
Ontario	http://www.mto.gov.on.ca/english/trucks/
Quebec	https://www.transports.gouv.qc.ca/fr/modes-transport-utilises/vehicules-lourds/Pages/vehicules-lourds.aspx
New Brunswick	http://www2.gnb.ca/content/gnb/en/departments/dti/trucking.html
Prince Edward Island	http://www.gov.pe.ca/law/regulations/pdf/R&15-5.pdf
Nova Scotia	http://www.gov.ns.ca/tran/trucking/vehiclewghtsdims.asp
Newfoundland and Labrador	http://www.hoa.gov.nl.ca/hoa/regulations/rc010081.htm#5
Yukon	http://www.gov.yk.ca/services/cat_trans.html
Northwest Territories	http://www.justice.gov.nt.ca/

TABLE A3.4 Provincial and Territorial Regulation Information

SOURCE: HTTPS://WWW.COMT.CA/ENGLISH/PROGRAMS/TRUCKING/STANDARDS.HTM

It should be recognized that each jurisdiction retains the authority to allow more liberal weights and dimensions, or different types of vehicle configurations, within their jurisdiction. [**61**]

TABLE A3.4 provides quick links to specific provincial and territorial information. [**62**]

A3.4 Vehicle Classification Using FHWA 13 Category Scheme

The FHWA vehicle classification scheme separates vehicles into categories depending on whether they carry passengers or commodities. Non-passenger vehicles are further subdivided by the number of axles and the number of units, including both power and trailer units. As example Class 9 is a Single Trailer 5 Axle Truck, Class 10 is a Single Trailer 6 or 7 Axles Truck, Class 11 is a Multi Trailer with 5 or less Axle Truck, Class 12 is a Multi-Trailer with 6 Axle Truck and Class 13 is a Multi-Trailer 7 or more Axle Truck. **FIGURE A3.3** shows the 13 category scheme used. [**63**]

Traffic monitoring and weigh scale systems across the U.S. and Canada generally utilize this method of classification. [**64**]

There are many methods and associated variation in capturing results in classifying vehicles, measuring truck flow data, GVW values, number of axles and then calculating an Equivalent Single Axle Loading. Variation in data collected may influence the final accuracy of the data available for analysis especially when comparing results across jurisdictions.

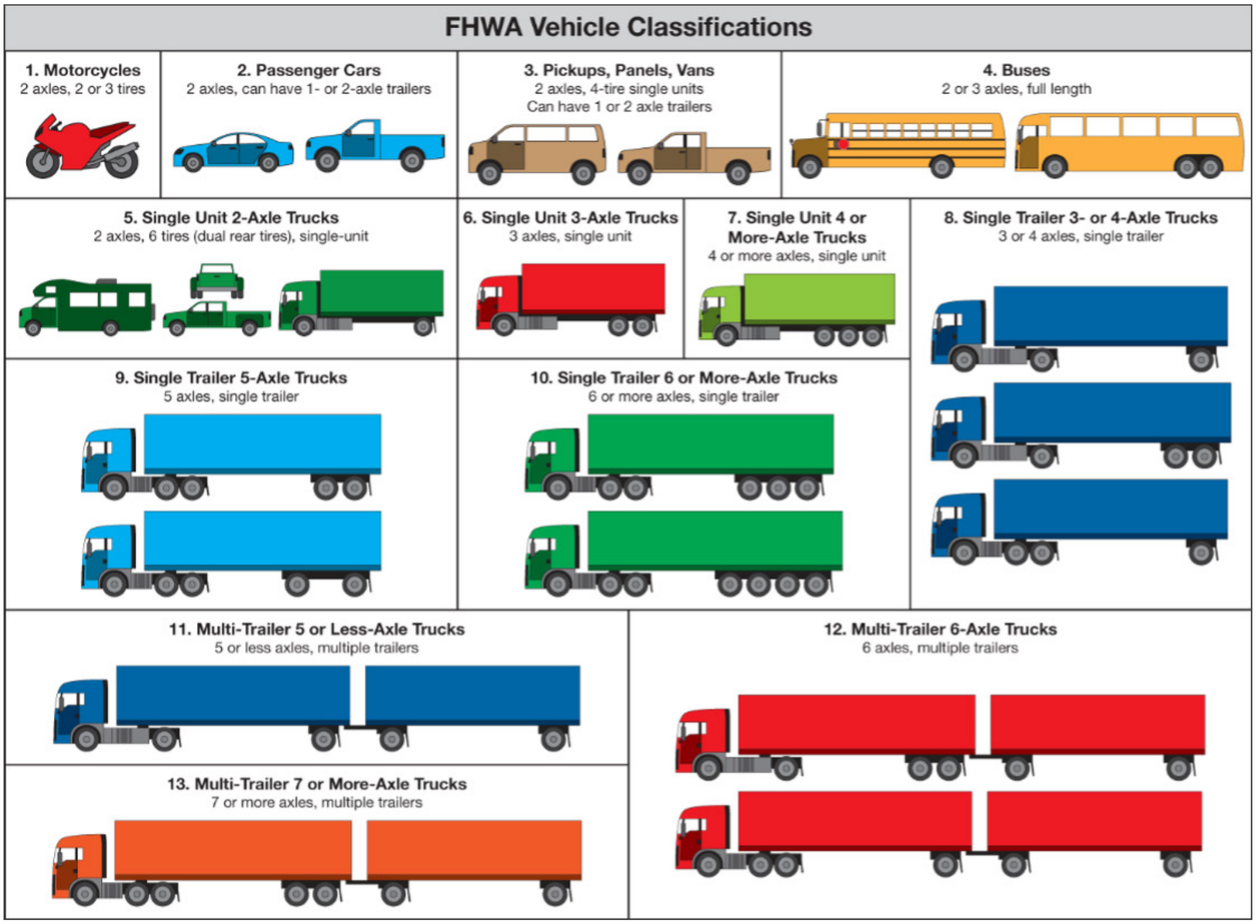
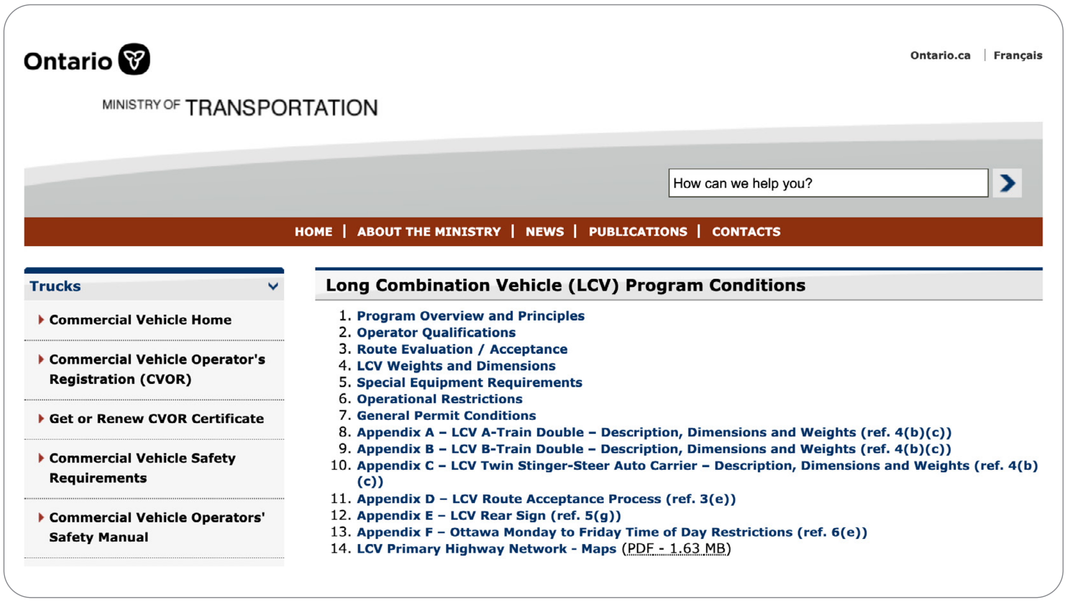


FIGURE A3.3 Vehicle Classification

SOURCE: HTTP://WWW.MTO.GOV.ON.CA/ENGLISH/TRUCKS/LONG-COMBINATION-VEHICLES.SHTML

A3.5 Ontario Long Combination Vehicle (LCV) Program

Ontario has defined very specific requirements relative to the safe operation of Long Combination Vehicles on provincial highways. The details can be found at http://www.mto.gov.on.ca/english/trucks/long-combination-vehicles-program-conditions.shtml



4. LCV Weights and Dimensions

No.	Item	P	Description
4(a)	Allowable LCV Types	P P P	• A-Train Double consists of a 3-axle tractor, a tandem or tridem-axle lead semi-trailer, a tandem-axle converter dolly and a tandem or tridem-axle second semi-trailer. Both rear axles of tractor must be drive axles. • B-Train Double consists of a 3-axle tractor, a tridem-axle lead semi-trailer and a tandem or tridem-axle second semi-trailer. Both rear axles of tractor must be drive axles. • B-trains comprised of two 16.2 metre long trailers are not currently allowed in the Program. • Twin Stinger-Steer Auto Carriers consist of a 3-axle tractor, a triple-axle equipped lead semi-trailer where the rear-most axle is liftable, and a tandem-axle second trailer. Both rear axles of the tractor must be drive axles.
4(b)	Allowable Dimensions	P P	• Allowable dimensions for the A-Train Doubles, B-Train Doubles and Twin Stinger-Steers are as specified in Appendices A, B and C respectively. • Aerodynamic devices at rear of trailers are excluded from length measurements provided they are authorized by and meet all conditions of a separate vehicle or fleet permit or meet requirements specified in the Highway Traffic Act.
4(c)	Allowable Weights	P P	• Maximum tire, axle and gross weights for the A-Train Doubles, B-Train Doubles and Twin Stinger-Steers are as specified in Appendices A, B and C respectively. • The allowable gross weight of any A- or B-Train LCV combination must not exceed 63,500 kg. The allowable gross weight of any stinger-steer LCV combination must not exceed 55,000 kg.

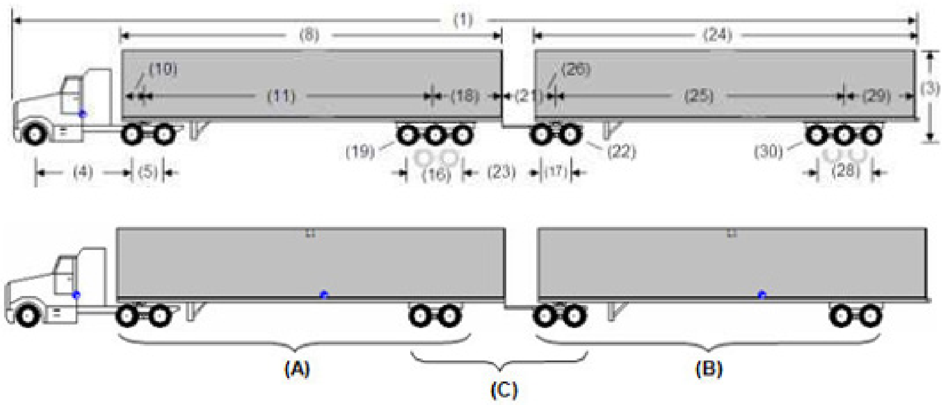


FIGURE A3.4 LCV A-Train Double — Description, Dimensions and Weights

LCV A-Train Double — Description, Dimensions and Weights[1]

Combination Description: The LCV A-Train Double consists of a tractor and two semi-trailers connected by a converter dolly. The front axle of the tractor is a single axle with single tires and the drive axle is a tandem axle. The converter dolly has a tandem axle. The second semi-trailer has a tandem or tridem axle.

Alternative Configurations: See regulations for details.

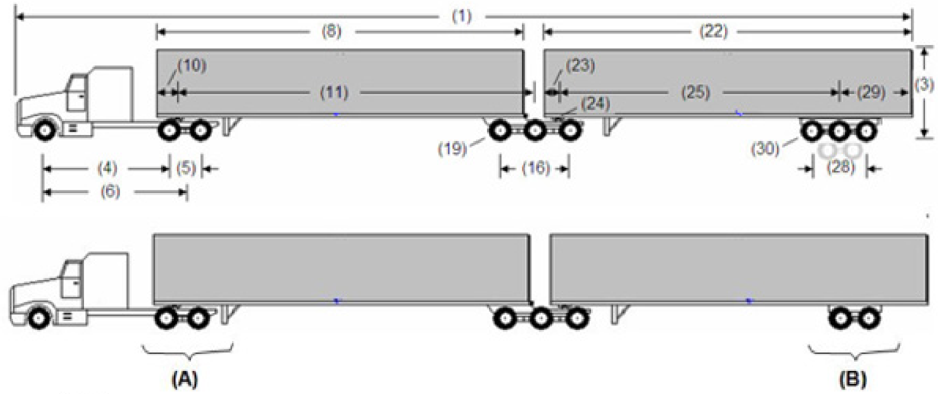


FIGURE A3.5 LCV B-Train Double — Description, Dimensions and Weights

LCV B-Train Double — Description, Dimensions and Weights[2]

Combination Description: The LCV B-Train Double consists of a tractor and two semi-trailers connected by a fifth wheel assembly whose lower half is mounted on the rear of the foremost semi-trailer. The front axle of the tractor is a single axle with single tires and the drive axle is a tandem axle. The lead semi-trailer has a tridem axle and the second trailer has a tandem or tridem axle.

Alternative Configurations: See regulations for details.

1 www.mto.gov.on.ca/english/trucks/long-combination-vehicles-program-conditions.shtml#appendix-a (Accessed, 25 June 2021).

2 www.mto.gov.on.ca/english/trucks/long-combination-vehicles-program-conditions.shtml#appendix-b (Accessed, 25 June 2021).

Section 3: A Review of Hydrogen as a Transportation Fuel
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[4] https://www.tc.gc.ca/media/documents/policy/2014_TC_Annual_Report_Overview-EN.pdf (Accessed, 26 April 2021)

[5] https://www.tc.gc.ca/media/documents/policy/2014_TC_Annual_Report_Overview-EN.pdf (Accessed, 26 April 2021)

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[7] http://www.ops.fhwa.dot.gov/freight/freight_analysis/nat_freight_stats/docs/13factsfigures/pdfs/fff2013_highres.pdf. (Accessed, 26 April 2021)

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[17] http://www.allstays.com/c/weigh-scales-ontario-locations-map.htm (Accessed, 26 April 2021)

[18] http://www.mto.gov.on.ca/iCorridor/map.shtml?accepted=true#tab_4 (Accessed, 26 April 2021)

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