Charting the Path to Zero Emissions for Class 8 Long-Haul Freight

Implementing Partners:

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Mobility Futures Lab

DELPHI

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About

Pollution Probe

Pollution Probe is a Canadian charitable environmental organization that is a leading agent of change at the intersection of communities, health and environment. Since 1969, we have been defining environmental problems through research, promoting understanding through education and pressing for practical solutions through advocacy. Pollution Probe has a proven track record of working in successful partnership with industry and government to develop practical solutions for shared environmental challenges.

Pollution Probe is one of Canada's leading independent transportation solution providers. Our work supports aggressive actions to address climate change and reduce air pollution while promoting job creation and economic growth. In addition to projects we actively contribute to expert transportation committees and working groups at local, regional, national and global levels. We are technology neutral and work collaboratively with a wide variety of stakeholders to develop transportation decarbonization solutions across all modes.

ACKNOWLEDGEMENTS

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Mobility Futures Lab

Mobility Futures Lab is a leading sustainable transportation consulting firm that is at the forefront of innovation and research in the field of mobility. The firm's services are designed to help clients navigate the complex landscape of sustainable transportation, with a focus on proprietary software tools and data-driven solutions. Our approach is based on a deep understanding of the interconnections between transportation, energy, and the environment.

DELPHI

Delphi provides strategic consulting services and innovative solutions to governments, public sector organizations, industry associations, and companies across Canada. Delphi is a recognized leader in corporate sustainability, clean technology and innovation, climate change, and the green and circular economy. As a pioneer in sustainability and environmental risk management, Delphi has helped some of Canada's best-known companies improve the sustainability of their organizations – as well as the local and global communities in which they operate. Over the past 30 years, we have provided bold solutions through more than 2,500 projects across all major sectors of the economy. Our clients benefit from the Delphi difference: we bring a unique combination of policy expertise, strategic thinking, and technical know-how to every project.

Executive Summary

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Background and Scope

The transportation sector is a significant contributor to greenhouse gas (GHG) emissions globally, with long-haul trucking playing a substantial role within this category. Class 8 long-haul trucks in Canada, designed for transporting goods over distances, predominantly utilize diesel fuel, leading to high GHG emissions and the release of harmful pollutants such as carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM). These emissions contribute to a range of health issues, particularly for populations residing near major highways. The growing awareness of the environmental and health ramifications of diesel exhaust and the urgent need to mitigate these impacts has catalyzed the exploration of zero emission vehicle (ZEV) technologies in the sector.

In response to these challenges, Pollution Probe, in collaboration with Delphi and Mobility Futures Lab and funded by the Natural Resources Canada (NRCan) Zero Emission Vehicle Awareness Initiative (ZEVAI), assessed the technological and market readiness of two leading ZEV options for Canada's Class 8 long-haul sector: hydrogen fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs). For the purposes of this assessment, diesel internal combustion engines (ICE) were considered to be the operational benchmark for heavy-duty, long-haul road transport (i.e., diesel ICE allows for sufficient payloads and range to be economical and operates within a well-established ecosystem).

The study involved extensive consultations with a diverse set of stakeholders, including original equipment manufacturers (OEMs), electrical utilities, hydrogen producers, fleet operators, and policymakers. This collaborative approach facilitated a detailed comparison of BEV and FCEV technologies, examining their operational capabilities, infrastructural requirements, and the current landscape of supporting policies and incentives. By evaluating the complexities and readiness of these technologies, the report aims to provide fleet operators and decision-makers with up-to-date, contextual information to inform the transition to zero emission freight transport in Canada.

Class 8 Zero Emission Technologies

Two primary pathways have been identified to decarbonize long-haul transport with ZEVs: BEVs, equipped with very large battery packs supported by a widespread network of high-powered public charging stations, and FCEVs, backed by a comprehensive national hydrogen distribution network. Both pathways entail significant upfront vehicle costs and require extensive development of supportive infrastructure. Cost parity with traditional segments is not anticipated until the next decade unless there is accelerated technological advancement or enhanced policy support.

ZEV readiness and support for long-haul operations

The potential breakthrough for long-haul BEVs hinges on the synergy of advancements in battery technology and industry innovations, such as the widespread adoption of megawatt fast charging stations and the infrastructure to support them. These advancements are crucial for mitigating issues related to range limitations and decreased payload for the portion of the long-haul sector operating at maximum weight load capacity. Similarly, while hydrogen fuel cell powertrains are operationally closer to the benchmark in areas such as range and payload, significant breakthroughs in the hydrogen fuel sector, particularly in green hydrogen production (e.g., developing electrolysis sites powered by renewable energy), are needed to reduce the cost of fuel, thereby enhancing the overall viability of hydrogen fuel cell trucks. Additionally, the development of a comprehensive hydrogen distribution infrastructure is essential to support the widespread adoption of these vehicles.

To foster these necessary breakthroughs and steer the market towards a zero-emission trajectory, two areas of support are critical – policy and incentives. Regulation can help close the gap between diesel ICE vehicles and ZEVs by promoting the development and manufacturing of alternative technologies. For example, tailpipe emissions regulations accelerate the adoption of battery electric and hydrogen fuel cell powertrains. Sales mandates can also play a role, providing reassurance to stakeholders and facilitating proactive infrastructure investments (hydrogen networks or grid upgrades).

Despite emerging supportive regulations, the current cost of ownership for Class 8 long-haul zero-emission vehicles is higher than that for ICE trucks. The deployment of new technology also requires in-depth real-world testing to mature. It is therefore imperative for governmental bodies to continue providing financial incentives for demonstration projects that can help fleet operators learn about the technology and aid in maturing the models being developed by OEMs through real-world operations in the Canadian context. Additionally, the continued expansion of renewable energy-based electricity generation and transmission projects, along with enhanced green hydrogen production and distribution networks, is essential for supporting the transition to decarbonized long-haul transport.

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Acronym List

ACF – Advanced Clean Fleets

ACT – Advanced Clean Trucks

AZETEC – Alberta Zero Emissions Truck Electrification Collaboration

BEVs – Battery Electric Vehicles

CAC – Criteria Air Contaminant

CARB – California Air Resources Board

CCS – Combined Charging System

CO – Carbon Monoxide

CO_2 – Carbon dioxide

CVP – Commercial Vehicle Pilot Program

DCFC – Direct Current Fast Charging

ECCC – Environment and Climate Change Canada

FCEVs – Hydrogen Fuel Cell Electric Vehicles

GHG – Greenhouse Gas

Global MOU – Global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles

HDV – Heavy-Duty Vehicle

HDZEV – Heavy-Duty Zero Emission Vehicle

ICE – Internal Combustion Engine

iMHZEV – Incentives for Medium- and Heavy-Duty Zero-Emission Vehicles Program

ITC – Investment Tax Credit

M2FCT – Million Mile Fuel Cell Truck Consortium

MCS – Megawatt Charging System

MHDV – Medium and Heavy-Duty Vehicle

MOU – Memorandum of Understanding

MY – Model Year

NMHC – Nonmethane hydrocarbon

NOx – Nitrogen Oxides

NRCan – Natural Resources Canada

OEMs – Original Equipment Manufacturers

PM – Particulate Matter

R&D – Research and Development

U.S. – United States

ZETP – Zero-Emission Trucking Program

ZEV – Zero Emission Vehicle

ZEVAI – Zero Emission Vehicle Awareness Initiative

ZEVIP – Zero Emission Vehicle Infrastructure Program

1 Introduction

Class 8 long-haul trucks in Canada, defined as vehicles exceeding a 14,969 kg (33,000 lbs) weight limit and designed for transporting goods over long distances typically greater than 500 kilometers, are predominantly powered by diesel. In 2022, Canada's Class 8 truck operating population stood at 369,000 vehicles, and it is anticipated to increase to 380,000 by 2027.[1] A portion of this fleet operates in regional travel and the other in long-haul, with an unclear distribution at this stage. Within Canada's medium and heavy-duty vehicle (MHDV) sector, these trucks represent the highest greenhouse gas (GHG) emitting segment, attributed to their significant yearly travel distances and substantial load capacities. Diesel exhaust, a byproduct of their operation, contains harmful pollutants including carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM). The health implications of exposure to these pollutants are increasingly recognized, particularly in terms of worsening cardiovascular and respiratory illnesses, especially for residents living near highways where these trucks frequently operate.[2] The impacts of diesel exhaust from long-haul trucking on the general population's health are increasingly understood, highlighting the urgency in addressing emissions from this sector.

Hydrogen fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs) are the two leading zero emission vehicle (ZEV) technologies suitable for large-scale adoption in long-haul trucking operations. In this context, 'zero emission' specifically means there are no tailpipe emissions, which is crucial for reducing air pollution.

It is important to recognize that the environmental impact of BEVs depends on the energy sources of the local electrical grid, which can vary significantly across different regions. Some areas benefit from cleaner, renewable energy sources, leading to fewer indirect emissions, while others rely more heavily on fossil fuels for electricity generation, resulting in higher indirect emissions. The environmental footprint of FCEVs largely depends on the method of hydrogen production. In this report, when we refer to the use of hydrogen, we specifically mean 'green hydrogen,' which denotes hydrogen produced via the electrolysis of water using renewable energy. This method is considered the most environmentally friendly, as it produces the least emissions compared to other hydrogen production methods.

1 Truck News (2023). Heavy-duty aftermarket continues to grow as economy slows. Retrieved from: https://www.trucknews.com/business-management/heavy-duty-aftermarket-continues-to-grow-as-economy-slows/1003171991/#:~:text=Canada%20had%20a%20total%20Class,climb%20to%20589%2C000%20in%202027.

2 Pan, S., Roy, A., Choi, Y., Sun, S.Q., Gao, H.O., 2019. The air quality and health impacts of projected long-haul truck and rail freight transportation in the United States in 2050. Environ. Int. 130. https://doi.org/10.1016/j.envint.2019.104922

Significant debate exists in the Class 8 long-haul market segment between FCEV and BEV technology. Prior to recent cost reduction developments in the battery industry, BEVs have long been considered unfeasible for this market segment, as the power requirements of these vehicles would require very large, costly, and heavy batteries, which could reduce the available payload capacity for long-haul trucks operating at existing weight limits. High power charging infrastructure is also cited as a significant barrier to long-haul electric trucks from a technological and financial standpoint. Given that hydrogen tanks can be filled quickly, minimizing time off the road, FCEVs have often been considered a promising ZEV technology, but hydrogen requires significant energy to produce, as well as a costly network of related infrastructure that doesn't exist today. [3]

As of 2024, many truck manufacturers are still betting that the future of long-haul trucking is FCEVs. Others are putting their chips on BEVs, believing that battery technology advancements in the coming decade will make them the powertrain of choice for trucks from delivery vans to powerful semis. Fleet operators and decision makers currently lack up to date information on the developments of each technology, and the implications of their adoption in the Canadian context.

In this context, Pollution Probe, in partnership with Delphi and Mobility Futures Lab received funding from the NRCan Zero Emission Vehicle Awareness Initiative (ZEVAI) to conduct a technology and market readiness assessment comparing FCEV and BEV technology in the Class 8 long-haul sector in the Canadian context. The project involved consultations with stakeholders including original equipment manufacturers (OEMs), electrical utilities, hydrogen production companies, fleet operators and policy makers. This side-by-side comparison of Class 8 long-haul BEVs and FCEVs addresses opportunities, challenges, and necessary considerations for adoption of both technology options.

The technology assessment evaluates BEV and FCEV technologies, examining their development progress, current status, and future needs. It covers both vehicle and charging/refueling infrastructure innovations. The report also discusses the complexities of required infrastructure developments for these technologies in Canadian long-haul corridors, along with preliminary developments in various provinces. The market readiness assessment evaluates the potential success of these technologies, considering factors like production capacity, cost analysis, and relevant regulations and incentives, including federal and provincial incentives and rules designed to advance the adoption of zero emission Class 8 long-haul vehicles in Canada.

3 NACFE (2023). The Messy Middle: A Time for Action. Retrieved from: https://nacfe.org/research/thought-leadership/the-messy-middle/

2 Technology Capabilities

2.1 Battery Electric and Hydrogen Fuel Cell Technologies

Battery electric trucks use lithium-ion batteries to store electrical energy (Figure 1). An electric motor powers the vehicle by converting stored electricity into motion. These trucks require large battery packs to achieve the necessary range for long-haul applications, and the energy to charge them is typically supplied by the electrical grid. A battery management system plays a crucial role in monitoring and controlling the performance, health, and safety of the battery pack, ensuring optimal energy efficiency, and safeguarding against potential issues such as overcharging, overheating, and overall degradation.

Figure 1: Battery Electric Truck Configuration [4]

Hydrogen fuel cell trucks generate electricity on board by combining hydrogen gas stored in high-pressure tanks with oxygen in a fuel cell stack, initiating a chemical reaction that produces electrical energy for the truck's electric motors (Figure 2). In configurations where the fuel cell is dominant, the primary propulsion power comes from the fuel cell, supplemented by a smaller battery pack used for energy recovery and to provide additional power during peak demand. Conversely, a battery dominant design relies primarily on a larger battery pack for propulsion. Certain FCEV exhibit flexibility by operating in various modes, allowing them to select between fuel cell and battery power, or a combination of both, adapting to different proportions based on the vehicle's duty cycle and status.

PHOTO: GETTY IMAGES/ SCHARFSINN86

4 Cleantechnica (2022). Tesla Semi Details Revealed in Parts Catalog Diagrams. Retrieved from: https://cleantechnica.com/2023/01/05/tesla-semi-details-revealed-in-parts-catalog-diagrams/

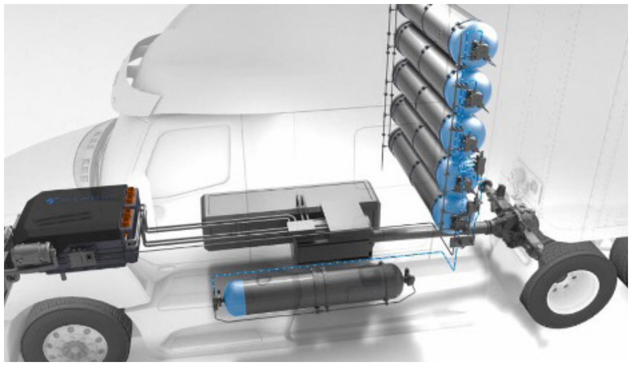


Figure 2: Hydrogen Fuel Cell Truck Configuration [5]

Battery electric trucks offer superior energy efficiency to alternative technologies, ranging from 65% to 85% from the charger to the wheels.[6] In comparison, ICE trucks exhibit efficiency rates of 40% to 50%, while hydrogen fuel cell trucks range from 30% to 50%.[7] Both FCEVs and BEVs employ electric drivetrains. However, the process of converting hydrogen from sources like water, compressing it for vehicle use, and then converting it back into electricity results in multiple energy-consuming steps, making hydrogen less efficient as a fuel source for vehicles compared to directly using electricity from the grid to power BEVs.

2.2 Operational Considerations

Long-haul trucking is a critical part of Canada's freight supply chain. The Trans-Canada Highway, stretching over 7,800 kilometers from the west coast of British Columbia to the east coast of Newfoundland and Labrador, serves as a key artery for trucking routes (Figure 3). These routes include major corridors such as Highway 401 in Ontario, Highway 17 in northern Ontario, Highway 2 in Alberta, Highway 16 in the western provinces, and Highway 20 in Quebec. Due to the country's expansive geography, long-haul truckers navigate diverse weather conditions and terrains, covering extensive distances from the Rocky Mountains to the Prairies and the Canadian Shield, ensuring the efficient movement of goods across the nation.

The trucking industry is a key component of Canada's economy, facilitating the movement of goods between provinces and to and from the United States. The profession of long-haul truck driving in Canada comes with its own set of challenges, including navigating through remote areas, dealing with weather extremes, and adhering to strict regulations governing driving hours and rest breaks. The demand for skilled and reliable truck drivers remains high, and the industry continues to evolve with advancements in technology, logistics, and efforts to enhance environmental sustainability.

In Canada, long-haul truckers typically cover 650 to 1,100 kilometers per day, adhering to Transport Canada and provincial/territorial regulations. Driving hours are capped at 13 hours in a day, with mandatory breaks within the first eight hours of driving. Communication and documentation, including the use of electronic logging devices, are essential for coordinating with dispatchers and ensuring compliance. Overnight stops, rest periods, and accurate record-keeping are integral to a truck driver's routine, with regulations subject to updates that drivers must stay informed about.

< Figure 3: Canadian National Highway System [8]

5 Transport for NSW (2023). Fuel cell electric vehicles (FCEV). Retrieved form: https://www.transport.nsw.gov.au/operations/freight-hub/towards-net-zero-emissions-freight-policy/knowledge-hub/fuel-cell-electric

6 "From the charger to the wheels" refers to the efficiency with which electrical energy is converted into mechanical energy to propel the vehicle, from the initial electric charge to the actual rotation of the wheels.

7 NACFE (2023). The Messy Middle: A Time for Action. Retrieved from: https://nacfe.org/research/thought-leadership/the-messy-middle/

8 Transport Canada (2020). The National Highway System (NHS) Map. Retrieved from: https://tc.canada.ca/en/corporate-services/policies/national-highway-system-nhs-map

2.2.1 Range

Long-haul diesel trucks can cover distances of up to approximately 1,600 km before requiring a refill. Class 8 FCEV trucks have an average range of approximately 680 km versus 350 km for BEV trucks, based on models released and planned for production in North America. Figure 4 presents the listed range of Class 8 battery electric and hydrogen fuel cell trucks in production or planned for production in the coming years in the North American Class 8 market. FCEVs can achieve a greater range relative to BEV technology due to the capacity of the hydrogen tanks to hold more energy than batteries. Cold temperatures and extreme weather can impact BEV ranges, though there is no publicly available data to accurately quantify these effects in the Canadian long-haul context. FCEV trucks are expected to be less affected, primarily due to their reduced reliance on battery packs.

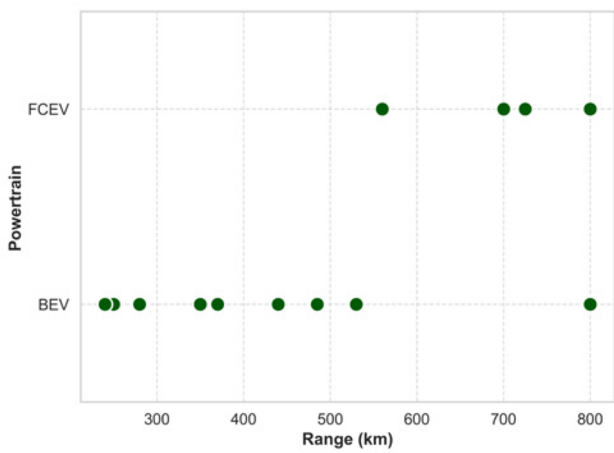


Figure 4: Range of battery electric and hydrogen fuel cell Class 8 tractor models available under various configurations to reach production by 2025 (each dot represents a model configuration)

BEV

The successful integration of Class 8 BEV trucks in long-haul transportation depends on deploying large batteries with sufficient range capacities. Existing Class 8 battery electric tractor trucks, with an average range of 350 km, are only suitable for regional return-to-depot hauling and not long-haul journeys.[9] The larger batteries necessary for long-haul freight increase vehicle weight, impacting the payload capacity of the trucks. This creates a dilemma: choose smaller batteries, requiring fast but currently unavailable charging at rest stops, or invest in oversized batteries, exacerbating weight and cost concerns. This delicate balance between range and payload is further complicated by the impact of extreme weather conditions on BEV range.

FCEV

There are two pressure options for storing compressed hydrogen in trucks: 350 bar and 700 bar technologies. 350 bar storage is standard for FCEV buses with ranges of up to 400 km but is not sufficient for long-haul trucks. The 700-bar compressed hydrogen gas option offers increased range (average of 700 km), thanks to higher volumetric density, but at higher cost. This option is currently under consideration for the Class 8 long-haul trucking sector. Liquid and cryo-compressed hydrogen storage technologies, which cool and compress hydrogen to even higher pressures, significantly increase storage density. They offer the greatest driving ranges, currently achieving distances of 800–900 km and expected to surpass 1,000 km by 2030, but present additional challenges due to the requirement to maintain very low temperatures.[10]

There are a number of demonstration projects and instances of real-world testing taking place in Canada and the U.S. for both BEV and FCEV Class 8 trucks. The tests are helping to verify the ranges and other performance measures of the trucks.[11] Further details about these demonstrations can be found in 3.2 Commercial Availability.

2.2.2 Payload

Heavy-duty commercial vehicles are required to comply with regulated weight limits, ensuring that each vehicle stays within a specified gross weight. Weight regulations by jurisdiction are outlined in Section 3.1.3. Subtracting the unloaded vehicle weight from the gross weight regulations results in the available freight weight. The federal U.S. weight limit is 36,500 kg (80,000 lbs); however, a number of State laws exceed that – even more than doubling it.[12] In Canada, weight regulations set by the provinces can reach up to 63,500 kg (140,000 lbs).

9 Forbes (2023). Tesla Isn't The Only Company Offering Electric Class 8 Trucks. Retrieved from: https://www.forbes.com/sites/michaelharley/2023/09/24/tesla-isnt-the-only-company-offering-electric-class-8-trucks/?sh=17a01acb8c24

10 ICCT (2022). Fuel cell electric tractor-trailers: Technology overview and fuel economy. Retrieved from: https://theicct.org/publication/fuel-cell-tractor-trailer-tech-fuel-jul22/

11 TruckNews (2023). $3 million invested in zero-emission trucking projects including new testbed. Retrieved from: https://www.trucknews.com/sustainability/3-million-invested-in-zero-emission-trucking-projects-including-new-testbed/1003177774/

12 BigTruckGuide (2016). Semi truck size and weight laws in the United States and Canada. Retrieved from: https://www.bigtruckguide.com/semi-truck-size-and-weight-laws-in-the-united-states-and-canada/

Industry and interview data suggest that the majority of freight carried in the U.S. remains below the maximum U.S. weight limit, however definitively stating whether a long-haul freight truck is operating at full capacity is challenging. This is because some shippers consolidate orders to maximize space utilization not always reaching full loads, while others only ship full loads, leading to variability in truck utilization. Detailed data on the loads carried across Canada is proprietary and not widely available, except for British Columbia, where it is estimated that 32% of Class 8 trucks operate above the U.S. weight limits, according to provincial weight scale data.[13]

Class 8 FCEV and BEV trucks are primarily being developed to meet the U.S. weight limits of 36,500 kg (80,000 lbs). Both technologies are expected to be heavier than their diesel ICE counterparts and therefore lead to payload reductions. FCEV trucks are expected to weigh on average 3,520 kg (7,750 lbs) more than an ICE truck due to the added weight of high-pressure hydrogen tanks. Hydrogen's lower volumetric density and the pressure requirements compared to diesel require additional weight on the vehicle for fuel storage. Liquid hydrogen can mitigate this issue; however, it introduces additional complexities to the overall system (e.g cooling to and maintaining at a temperature below negative 253 degrees Celsius). Production-scale improvements are anticipated to reduce this weight penalty to 1,800 – 2,300 kg (4,000-5,000 lbs) due to weight reductions in the components of the vehicles.[14]

In long-haul operations for Class 8 BEV trucks, payload capacity is linked to battery size, which varies based on range requirements. The choice of battery size is also influenced by the availability and effectiveness of large power chargers for rapid charging. Effective rapid charging infrastructure could make smaller batteries more viable, as they could be recharged quickly during more frequent stops. For 400 to 600 km ranges, Class 8 BEV trucks are projected to weigh, on average, 3,150 to 6,350 kg (7,000 – 14,000 lbs) more than diesel trucks. As the range of the vehicle increases further, the payload must be further limited to accommodate bigger batteries. This relationship is crucial in understanding the impact of varying ranges on payload capacity in long-haul operations for battery electric trucks.[15] Advances in battery chemistries are expected to reduce this weight penalty to 1,939 kg by 2050.[16]

Given that a portion of long-haul trucks in Canada carry heavier loads than those in most U.S. states due to higher Canadian weight limits, these increased loads demand more robust power solutions, leading to higher hydrogen or energy consumption by vehicles. This presents an additional challenge for the integration of zero-emission technologies in the Canadian context, necessitating special testing. Such testing is required for commercially available trucks to be certified to haul at Canadian weights and dimensions.

2.3 Infrastructure Requirements

Long-haul trucking operations will require charging and refueling stops that align as much as possible with the standard duration of rest stops. This will ensure that the transition will not impose additional staff time costs on trucking companies due to prolonged charging or refueling times.

2.3.1 Charging Infrastructure

2.3.1.1 Electricity generation and distribution

Class 8 BEV models are expected to have batteries that are 10 to 15 times larger than light duty passenger vehicles. The impact of the electrification of Class 8 long-haul vehicles on the electricity system is not as well understood or as studied as it has been for light-duty vehicles.[17] There are two issues related to the electrification of heavy-duty transportation. First, the amount of energy that is required to meet the incremental demand for electricity for transportation, generally measured in MWh. Second, the power that is required – the rate at which the energy is consumed, typically measured in MWs. In other words, the electricity system needs to ensure it can both supply the total energy that will be required, and that the power is available to charge the vehicles.

13 British Columbia Trucking Association (2024). Pathway to achieving BC's heavy-duty trucking 2030 climate targets. Retrieved from: https://www.cleancarrier.ca/wp-content/uploads/2024/02/BCTA-White-Paper-2024.pdf

14 NACFE (2020). Making sense of Heavy-Duty Hydrogen Fuel Cell Tractors. Retrieved from: https://nacfe.org/downloads/making-sense-of-hydrogen-fuel-cell-tractors/

15 NACFE (2019). Viable Class 7/8 Electric, Hybrid and Alternative Fuel Tractors. Retrieved from: https://nacfe.org/wp-content/uploads/2024/05/Viable-Class-7-8-Alternative-Vehicles-Final-12-10-_compressed.pdf

16 Harvey, J.; Saboori, A.; Miller, M.; Kim, C.; Jaller, M.; Lea, J., et al. (2020). Effects of Increased Weights of Alternative Fuel Trucks on Pavement and Bridges. UC Office of the President: University of California Institute of Transportation Studies. Retrieved from: http://dx.doi.org/10.7922/G27M066V

17 Brennan Borlaug, et al. (2021). Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems, Nature Energy, Vol. 6. Retrieved from: https://doi.org/10.1038/s41560-021-00855-0

Stakeholders consulted indicate that increasing electricity generation is not a significant barrier if demand is adequately predicted. In a study on the electrification of heavy-duty vehicles in the European Union by the association of European grid operators, it was foreseen that the electrification of heavy-duty vehicles would only account for 3% of total electricity consumption in 2030, and this would not be a significant challenge. However, the transmission and distribution of electricity remain issues, as the additional power demand, particularly regarding grid availability and capacity, is expected to be a significant challenge.[18]

2.3.1.2 Development of charging infrastructure

In order to accommodate the charging of large batteries during the relatively short duration of drivers' mandatory rest stops on long-haul travel, charging locations will need to provide very high-power loads for fast charging. National Grid, a U.S. electric and gas utility, sees the potential for large truck charging stops having a power demand approaching that of a small town.[19] National Grid also analyzed the capacity for distribution circuits to accommodate fleet electrification in select areas. Based on their analysis, 68% of current distribution feeders in the region they evaluated would be overloaded or at risk of being overloaded at times of peak demand in the distribution system (either summer or winter), some requiring two to three times expansion in their capacity, with total expansion ranging from 1 to over 20 MW.[20] These investments will also likely include the long-distance transmission of power and distribution to local sites (Figure 5) that can be time-consuming and expensive. The exact costs and timing for any electrification project will depend on the existing connection the location has, the infrastructure developed in the area, and the distance to substations.

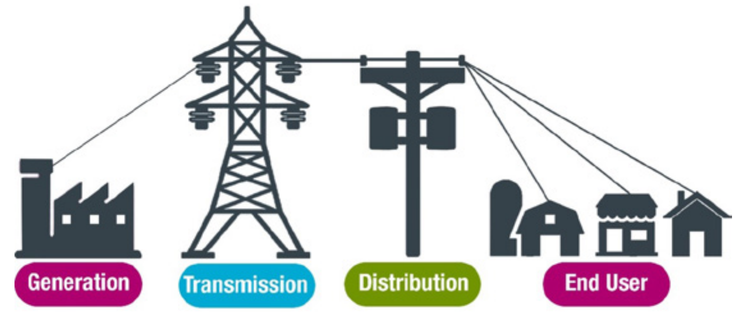


Figure 5 Electricity Industry Key Sectors. [21]

Long-haul trucking charging infrastructure would need to be developed at regular and suitable locations along freight corridors.[22] Charging hubs proposed in Europe range from 1.8 MW to 8.4 MW, which will require a medium-voltage connection at 10-35 kV.[23] As responsibilities for managing the grid differ across jurisdictions, planning the grid connection for a charging station may require coordination with several companies.[24]

The electrification of heavy-duty transportation will require significant capital investments by electrical utilities in transmission and distribution infrastructure. It will be up to utilities, policymakers, and regulators to plan for the capital investments in a way that avoids delaying the transition to electrification, while at the same time not investing in assets long before they are used, or potentially even not used if the demand does not materialize. Utilities will have to plan and construct infrastructure to allow a significant number of long-haul trucks to charge simultaneously using very high-power loads along freight corridors in locations that did not previously require this much power.[25]

18 ENTSO-E (2023). Position paper on "Deployment of Heavy-Duty Electric Vehicles and their Impact on the Power System". Retrieved from: https://www.entsoe.eu/2023/10/06/position-paper-on-deployment-of-heavy-duty-electric-vehicles-and-their-impact-on-the-power-system/

19 Tom Randall (2022). Electric Truck Stops Will Need as Much Power as a Small Town, Bloomberg News. Retrieved from: https://www.bnnbloomberg.ca/electric-truck-stops-will-need-as-much-power-as-a-small-town-1.1846067.

20 National Grid, Hitachi (2021). The Road to Transportation Decarbonization: Understanding Grid Impacts of Electric Fleets. Retrieved from: https://www.nationalgridus.com/media/pdfs/microsites/ev-fleet-program/understandinggridimpactsofelectricfleets.pdf

21 Utilities Consumer Advocate (2023). Understanding the Electricity Market. Retrieved from: https://ucahelps.alberta.ca/electricity-energy-market.aspx

22 In March 2024, the U.S. Joint Office of Energy and Transportation, the U.S. Department of Energy, the U.S. Department of Transportation and the Environmental Protection Agency released the National Zero-Emission Freight Corridor Strategy. The Strategy "lays out an all-of-government approach to aligning investments and accelerating sustainable and scalable deployment of reliable ZE-MHDV infrastructure." The Strategy demonstrates the potential for a phase-in approach over time, targeting priority areas, including key freight corridors and hubs. Source: Kang-Ching Chu et al. (2024). National Zero-Emission Freight Corridor Strategy. Retrieved from: https://driveelectric.gov/files/zef-corridor-strategy.pdf

23 Karsten Burges, et al. (2023). Grid Readiness for HDV Charging: a Survey among European DSOs on behalf of Transport and Environment. Retrieved from: https://www.transportenvironment.org/wp-content/uploads/2023/08/2023_07_TE_AFIR_grid_readiness_final.pdf

24 In Ontario, for example, lines above 50 kV are maintained by the transmission operator.

25 Information from stakeholder interviews

2.3.1.3 Managing infrastructure costs

As discussed above, extensive capital investments will be required to construct a charging network to allow for long-haul vehicles. In most cases electricity network operators do not proactively build their networks for anticipated demand; rather the regulatory construct means that they wait for connections requests to come in before they seek regulatory approval for capital expenditure. Such policy ensures that utilities do not invest in assets that may not get used as anticipated, which would lead to higher costs for all customers, but this policy can lead to long delays for approvals before construction or procurement can begin. In some cases, political direction has given utilities in specific jurisdictions permission to proactively prepare their networks for transportation electrification, thereby allowing for capital expenditures in anticipation that the market will develop, and that demand will increase;[26] however, such proactive capital expenditures remain rare.

In the case that grid upgrades are completed in response to a connection request, costs are usually charged to the customer requiring the power at that time, despite the fact that future customers may be able to benefit from the upgrade.[27] Regardless of political direction for anticipatory capital expenditures, paying for grid infrastructure well before the demand materializes to create the market will be difficult to finance as the assets will not be fully used, and thus new financing mechanisms, or even government support, may be needed to ensure that the charging network is built out before the demand is actually there to ensure that others customer costs do not increase dramatically. Risks of stranded assets could be alleviated through planning and engagement with fleet operators and Class 8 vehicle operators. To mitigate such risks, in the U.S. vehicle manufacturers are partnering with utilities to create their own networks, for example Daimler with Greenlane.[28]

In addition, total capital costs for developing charging infrastructure will depend on the peak demand of the facility. If the peak demand can be reduced or flattened, costs can be mitigated. Fleets that have the opportunity to charge overnight at central hubs or depots can manage their charging and ensure that peak demand is controlled. Such managed charging will be more difficult for long-haul vehicles that need enroute charging at rest areas or other locations. An option would be to pair battery storage and a renewable energy source, likely solar power, to reduce the draw on the public grid. WattEV, a California supplier of truck charging stations, has received funding to develop two sites with 175 kW chargers and 17 MW scale charging stations. To offset the need for grid reinforcements, the site will incorporate 25 hectares of solar panels and 5.5 MWh of onsite battery storage.[29]

The Portuguese transmission system operator REN has been testing a tap that connects an existing high-voltage transmission line, through a special small substation, directly to EV charging points. This solution reduces infrastructure costs by avoiding any interaction with the distribution system, eliminating the need for substation upgrades. In addition, it enables charging directly from the high-voltage transmission grid, which could address challenges with weak distribution networks, particularly in remote areas.[30]

More research and demonstrations with end-users are necessary to fully understand the charging opportunities, costs, and framework conditions for enabling Class 8 BEV charging. Adequate analysis of projected demand in different locations is essential for long-haul trucks that will require extremely high power loads. Research is also required on how flexibility, innovation to reduce charging peaks, and different financing models can allow for a cost-effective deployment of charging infrastructure.

2.3.1.4 Charging stations

The design standards of the charging stations that can accommodate fast charging for Class 8 long-haul trucks are in the early stages of development. The CCS (Combined Charging System) Direct Current Fast Charging (DCFC) plug is the dominant plug for new battery electric trucks in the MHDV sector. However, there is a limit to the capacity of CCS connections.

26 Information from interviews

27 Tom Randall (2022). Electric Truck Stops Will Need as Much Power as a Small Town, Bloomberg News. Retrieved from: https://www.bnnbloomberg.ca/electric-truck-stops-will-need-as-much-power-as-a-small-town-1.1846067; National Grid, Hitachi (2021). The Road to Transportation Decarbonization: Understanding Grid Impacts of Electric Fleets. Retrieved from: https://www.nationalgridus.com/media/pdfs/microsites/ev-fleet-program/understandinggridimpactsofelectricfleets.pdf

28 Greenlane (2024). Zero emissions public charging and H2 fueling. Retrieved from: https://www.drivegreenlane.com

29 WattEV (2024). WattEV Secures Record-Breaking $75.6 Million in Federal Grants to Expand West Coast Electric Truck Charging Corridor. Retrieved from: https://www.wattev.com/post/wattev-secures-record-breaking-75-6-million-in-federal-grants-to-expand-west-coast-electric-truck-c

30 ENTSO-E (2023). Position paper on "Deployment of Heavy-Duty Electric Vehicles and their Impact on the Power System". Retrieved from: https://www.entsoe.eu/2023/10/06/position-paper-on-deployment-of-heavy-duty-electric-vehicles-and-their-impact-on-the-power-system/

The CCS DC plug tops out at around 350 kW and 500 amps. For medium duty trucks that is sufficient – with a 150-kWh battery vehicle requiring around 20 minutes to charge from 0 to 80%. Some trucking applications with high dwell times at depots can also use significantly lower (8 kW – 19 kW) AC charging power that accommodates their drive cycle. On the other hand, when it comes to long-haul Class 8 trucks making runs with short stops and at least 400-kWh in their batteries – 350kW would not be fast enough to accommodate the duration of mandatory rest stops of drivers during long-haul travel.

A larger power connector is therefore vital for making long-haul electric trucks time competitive with their diesel counterparts. A new Megawatt Charging System (MCS) is currently being developed to allow for a maximum current of 3,000 amps at 1,250V, resulting in a maximum charging power of up to 3,750 kW (3.75 MW), which would be suitable for long-haul trucking (Figure 6).

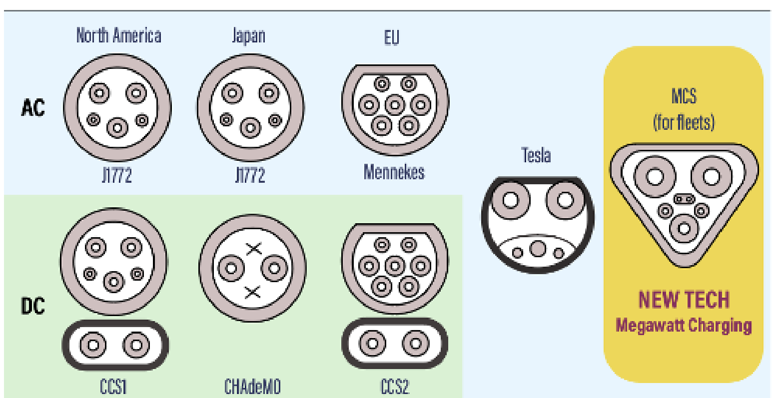


Figure 6 Charging Station Plugs. [31]

The MCS is an emerging standard aimed at providing high-powered charging capabilities beyond the current capacity of DCFC. The Charging Interface Initiative Task Force for Heavy Duty Charging for Commercial Vehicles is leading the development of this standard.[32] The MCS standard is still in the development phase, and there are currently no in-production vehicles capable of utilizing this standard. However, experimental and pilot charging at these elevated power levels has been conducted. The finalization of the MCS standard is anticipated in 2024. Once implemented in both chargers and vehicles, the high charging capacities could enable Class 8 battery electric trucks to charge rapidly, potentially making long-distance trips with battery electric trucks feasible as long as extensive investments are conducted for power upgrades. Figure 7 presents the charging power associated with different chargers used in the MHDV sector.

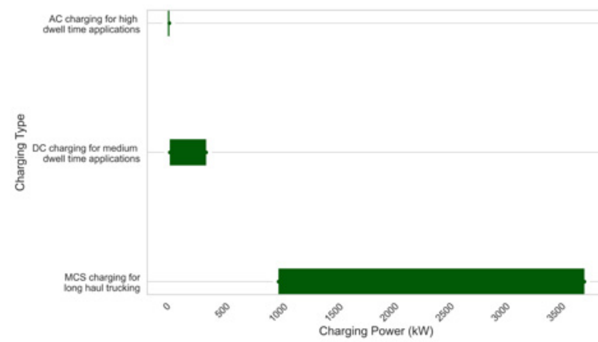


Figure 7 MHDV applications charging power

2.3.2 Hydrogen Refueling Infrastructure

2.3.2.1 Hydrogen production and distribution

The first barrier to the development of a hydrogen refueling system is ensuring there is sufficient hydrogen available. Hydrogen can be produced via several methods, each with varying emission intensities and costs. The decarbonization of the trucking sector with HFCVs will require increased adoption of the more costly green hydrogen produced through electrolysis. This will necessitate a significant increase in hydrogen production and the development of electrolysis sites along with accompanying renewable energy sources. If economic conditions align favorably with the needs of the long-haul transportation sector and other industries, this could drive a significant upswing in green hydrogen production. [33]

31 Solutions energy (2022). New Fleet Charger in Development. Retrieved from: https://www.solution.energy/post/new-fleet-charger-in-development

32 CharIN (2022). CharIN Whitepaper Megawatt Charging System (MCS). Retrieved from: https://www.charin.global/media/pages/technology/knowledgebase/c708ba33611670238823/whitepaper_megawatt_charging_system_1.0.pdf

33 At present, hydrogen is primarily produced through a carbon-intensive process using natural gas (SMR). To reduce costs in low-carbon hydrogen production methods, significant R&D investments are necessary, extending beyond the use of hydrogen solely in the transportation sector.

A number of clean hydrogen projects have been announced in Canada over the past few years to increase hydrogen production, including for transportation use.[34] These are expected to provide helpful case studies for the development of future hydrogen refueling infrastructure. [35]

Transport Canada regulates transport of gaseous hydrogen through the Transport of Dangerous Goods Regulations. Hydrogen for refueling stations can be produced on site, transported by truck as compressed gas or liquid, or distributed through hydrogen pipelines (Figure 8).

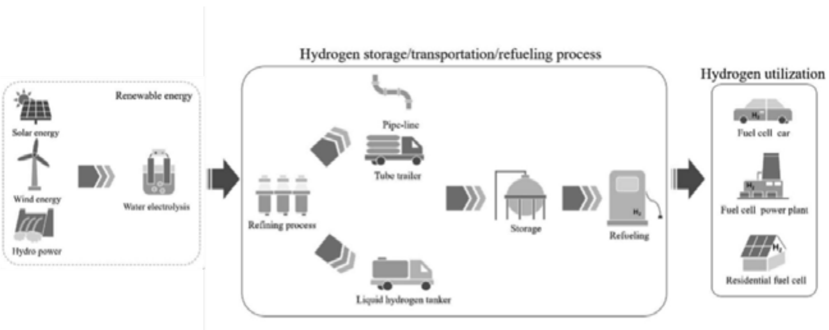


Figure 8 Hydrogen supply and refueling system [36]

Hydrogen is gaseous at atmospheric pressure and temperature, and thus transporting in its gaseous state is the most cost effective as it does not require additional energy for pressurizing or cooling. Pipelines can transport gaseous hydrogen and are thus ideal for transporting hydrogen for large dedicated fueling station demand (2,000 kg to 3,000 kg per day). However, pipelines entail significant capital investments. Studies are evaluating the potential of retrofitting existing natural gas pipelines for hydrogen and the expansion of existing pipeline infrastructure in the province of Alberta. [37]

Given the costs to construct or retrofit a pipeline system, trucking hydrogen could be a more cost-effective option. Tube trailers, which are heavy-duty vehicles that can carry gaseous hydrogen under pressure, are a cost-effective option, but as the hydrogen remains in a gaseous state there are limits to the quantity that can be transported in a single tube trailer. More hydrogen can be transported by liquid hydrogen vehicles, but transporting liquid hydrogen requires liquefaction plants and requires higher energy requirements, and hence higher costs, to maintain the low temperatures required.

There will likely be a combination of transportation methods. For example, in South Korea, which has one the largest hydrogen refueling networks in the world, 93% of hydrogen is supplied to refueling station by tube trailer, 4% of hydrogen from pipeline, and 3% of hydrogen is generated at the station. Table 1 summarizes the transportation options for hydrogen. [38]

Table 1 Comparison of hydrogen delivery options

State	Delivery method	Description
Gas	Pipeline	- Continuous supply regardless of scale and distance
		- Low energy loss
		- High fixed cost and low variable cost
	Tube trailer	- Suitable for low volume and intermittent supply of small/medium-scale refueling stations
		- Low energy loss
		- Low fixed cost and high variable cost
Liquid	Liquid truck trailer	- Must have access to liquefaction and storage facilities
		- Suitable for medium/large-scale and medium/long-distance
		- Additional GHG emissions due to electricity consumed during liquefaction
		- High energy loss
		- High fixed cost and low variable cost

34 Customized Energy Solutions (2023). Canada's Hydrogen Pathway. Retrieved from: https://ces-ltd.com/canadas-hydrogen-pathway/

35 Government of BC (2023). Province creating new opportunities in hydrogen economy, commercial trucking. Retrieved from: https://news.gov.bc.ca/releases/2023EMLI0064-001800

36 Adapted from Changjong Kim, et al (2022). "Review of hydrogen infrastructure: The current status and roll-out strategy," International Journal of Hydrogen Energy 48 (2023) 1701-1716. Retrieved from: https://doi.org/10.1016/j.ijhydene.2022.10.053

37 Natural Resources Canada (2020). Hydrogen Strategy for Canada. Retrieved from: https://natural-resources.canada.ca/sites/nrcan/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf

38 Changjong Kim, et al (2022). "Review of hydrogen infrastructure: The current status and roll-out strategy," International Journal of Hydrogen Energy 48 (2023) 1701-1716. Retrieved from: https://doi.org/10.1016/j.ijhydene.2022.10.053

2.3.2.2 Hydrogen station designs

The variability in hydrogen fueling station designs, influenced by factors such as size, operational and capital costs, and utilization, is a significant determinant of the delivered cost of hydrogen at the pump for transportation. Optimizing supply chains and leveraging manufacturing innovations could potentially cut hydrogen costs significantly, with research and development currently exploring the feasibility of scaling up stations through the use of compact components which would allow for more hydrogen refueling infrastructure on a set piece of land. Increasing station size would allow the station to supply more vehicles at any time thus increasing revenue. One advantage of hydrogen station design is that components can be modular, meaning that a station could start with one refueling system and one storage tank, adding more as demand increases. [39]

Light-duty vehicles and buses receive hydrogen at 700 bar and 350 bar, respectively. There is no standard yet for trucks. The 350-bar technology is more suitable for short-range operations that do not require high-pressure tanks, while the 700 bar technology would allow for more fuel delivered and shorter refueling time, desirable for long-haul operation.[40] It is estimated that a hydrogen refueling stations for long-haul trucking would require between 8,000 kg and 32,000 kg of hydrogen per day to refuel 150 to 650 trucks per day with an average fill of 50 kg. [41]

At present, Canada boasts eight hydrogen stations catering to retail needs, with the majority located in British Columbia. Additional stations are planned for construction across the country. These stations will be equipped to deliver from 100 kg to 1000 kg per day for both light and heavy-duty vehicles.[42]

Efforts to increase fueling rates are underway through the establishment of standards. The U.S. Department of Energy has set goals for heavy-duty trucks to reach fill rates of 8 kg H2/min by 2030 and 10 kg H2/min by 2050, envisioning a six-minute fill time for a 1,200 km range truck; meanwhile, ongoing research aims to validate proposed fueling standards and equipment. [43]

“The variability in hydrogen fueling station designs, influenced by factors such as size, operational and capital costs, and utilization, is a significant determinant of the delivered cost of hydrogen at the pump for transportation.”

39 Interview

40 ENTSO-E (2023). Position paper on “Deployment of Heavy-Duty Electric Vehicles and their Impact on the Power System”. Retrieved from: https://www.entsoe.eu/2023/10/06/position-paper-on-deployment-of-heavy-duty-electric-vehicles-and-their-impact-on-the-power-system/

41 Fuel Cell and Hydrogen Energy Association (2020). Road Map to a US Hydrogen Economy. Retrieved from: https://www.fchea.org/us-hydrogen-study

42 Hydrogen news (2022). Air Liquide contributes to the deployment of the heavy-duty hydrogen refueling infrastructure in Canada. Retrieved from: https://hydrogennews.airliquide.com/press-release-news/2022-08-31/air-liquide-contributes-deployment-heavy-duty-hydrogen-refueling-infrastructure-canada

43 One challenge associated with the transition to zero-emission vehicles is finding a replacement for the gas tax. It has been estimated that the federal government collects about $6 billion per year in gas and diesel excise taxes, excluding GST or HST on said purchases. Options to replace the tax include a flat fee (ex: a road-use fee) or a charge per distance traveled in the vehicle. Source: Peter Shawn Taylor (2022). Rise of electric vehicles raises tax concerns. Retrieved from: https://www.cpacanada.ca/news/pivot-magazine/2022-01-17-gas-tax-replacement

PHOTO: GETTY IMAGES/ JROBALLO

3 Market Developments

PHOTO: GETTY IMAGES/ KALAWIN

3.1 Regulations and Incentives

North American GHG and criteria air contaminant (CAC) regulations for HDVs are becoming increasingly stringent, opening the door to development and manufacturing of alternative technologies. For example, more stringent CAC regulations require manufacturers to develop emissions control devices (e.g., for NOx), which increase the cost of diesel trucks, making ZEV trucks more competitive. Tailpipe emissions regulations accelerate the potential, both operationally and economically, for alternative technologies, including BEVs and FCEVs. In addition, there has been a recent influx of financial support for research, development, deployment, and adoption of ZEV trucks (and related infrastructure), which can benefit both the developers and the purchasers of these technologies.

This section provides a high-level overview of relevant Canadian and U.S. regulations, as well as current incentive programs.

3.1.1 GHG Emissions Regulations

In Canada, tailpipe emissions for HDVs and engines are regulated by Environment and Climate Change Canada (ECCC) under the Canadian Environmental Protection Act, 1999 which limits GHG and CAC emissions. In 2013, Canada finalized the first phase of the Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations, which set GHG emission standards for heavy-duty vehicles and engines manufactured in, or imported into Canada, with model year (MY) 2014 and later. These regulations were updated in 2018 (as Phase 2 for MY 2021 and later) and last amended in October 2022. However, in response to a legal challenge in the U.S. related to their Phase 2 Rule, ECCC has issued six interim orders to suspend some of the provisions in Phase 2 (GHG emissions standards for trailers). [44]

The regulations in Canada have historically been aligned with the United States EPA national emissions standard, for medium- and heavy-duty vehicles. Alignment with the U.S. maximizes benefits for both countries as cross-border goods trade

44 Government of Canada (2024), Canada Gazette, Part I, Volume 158, Number 11: ORDERS IN COUNCIL. Retrieved from: https://www.gazette.gc.ca/rp-pr/p1/2024/2024-03-16/html/order-decret-eng.html

is optimized without the need to use different trucks, and operational and administrative costs are reduced. Table 2 presents an example of Canada and U.S. regulations regarding Class 8 tractors. Further details, including full references, can be found in Appendix A.

Table 2: Selection of GHG Emissions Limits

	Canada	United States	
Regulator	Environment and Climate Change Canada	Environmental Protection Agency and National Highway Traffic Safety Administration	
Regulations	Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations[45]	Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles (Phase 2[46]) (Phase 3[47])	
Coverage	GHG emissions	GHG emissions Fuel efficiency	
Emissions Standards Examples (Canada & U.S.)	**MY 2017 - 2020**	**MY 2021 - 2023**	**MY 2024 - 2026**
Class 8 Low Roof Sleeper Cab (g CO_2/ short ton-mile)	66	72.3	68
Class 8 High Roof Sleeper Cab (g CO_2/ short tone-mile)	72	75.7	70.7
Heavy-duty engine (used in tractors) (g CO_2/ bhp-hr)	460	447	436

3.1.2 CAC Emissions Regulations

Canada's current CAC emission standard for HDVs – On-Road Vehicle and Engine Emission Regulations – was published in 2003, and last amended in October 2022. For MY 2008 to 2026, the emissions limits are aligned with (and directly reference) the U.S. Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards (40 CFR Part 86). Table 3 presents Canada and U.S. regulations regarding CAC emissions limits for MY 2008-2026. Further details, including full references, can be found in Appendix A.

Following the U.S.'s lead, Canada is expected to update its regulations to further restrict CAC emissions from heavy-duty vehicles starting in MY 2027. This will further impact the ability of Class 8 diesel ICE trucks to economically meet regulations.

Table 3: Integrated U.S. and Canadian CAC Emissions Limits

CAC	NOx	NMHC	CO	PM
Emissions limit (g CAC/bhp-hr)	0.2	0.14	15.5 (compression-ignition) 14.4 (spark-ignition)	0.01

45 Government of Canada. Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations. SOR/2013-24. Current to March 20, 2024. Last amended on October 3, 2022. Retrieved from: https://laws-lois.justice.gc.ca/PDF/SOR-2013-24.pdf

46 Environmental Protection Agency. 40 CFR Parts 9, 22, 85, 86, 600, 1033, 1036, 1037, 1039, 1042, 1043, 1065, 1066, and 1068. Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 2. Retrieved from: https://www.govinfo.gov/content/pkg/FR-2016-10-25/pdf/2016-21203.pdf

47 Environmental Protection Agency. 40 CFR Parts 86, 1036, 1037, 1039, 1054, and 1065. Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3. Retrieved from: https://www.epa.gov/system/files/documents/2024-03/hd-phase3-veh-standrds-ghg-emission-frm-2024-03.pdf

3.1.3 Vehicle Weight Limits

Weight limits of long-haul trucks are different between the U.S. and Canada. In Canada, the weight limits fall under the authority of each Provincial and Territorial government which apply to the highways within their boundaries. In each Province/Territory, limits vary on configuration, such as number of axles and vehicle category. There are also seasonal weight restrictions in some jurisdictions (e.g., during spring thaw).[48] To enhance consistency in weight limits across jurisdictions in Canada, a Memorandum of Understanding (MOU) on Interprovincial Weights and Dimensions was initially introduced in 1988 and most recently amended in 2019. Under the MOU, maximum acceptable thresholds for the gross combination weight of seven commonly utilized Class 8 truck vehicle configurations were set, ranging from 24,250 kg (53,460 lbs) for a straight truck to 62,500 kg (137,800 lbs) for a B train double.[49]

Canadian limits allow for larger loads compared to federal U.S. regulated weight limit of 36,300 kg (80,000 lbs) for long-haul trucks operating on most federally funded highways, which include the interstates and national network of highways. While certain state laws exceed this national standard, federal regulations prevail in most locations. A high-level summary of Canada and U.S. truck size and weight allowance is provided in Table 4. The difference in the U.S. federal size and weight limit restricts the ability of carriers to take advantage of higher Canadian weight limits when moving freight via Class 8 truck from Canada into the U.S. Many early model ZEVs have been designed firstly for the U.S. market and may not be suitable for Canadian companies that have tuned their operations for Canadian weights.

When it comes to the adoption of ZEV technologies, weight limits will become even more important. As discussed in Section 2.2.2 Payload, ZEVs are heavier than standard ICE trucks, due to battery packs and hydrogen tanks. Modification of regulations to expand weight allowances for commercial vehicles will be crucial to foster ZEV technologies, primarily to compensate extra weight for the technologies in the short-term.

Several jurisdictions have already started adapting their regulations to accommodate ZEVs. For example, in the U.S., California allows near-zero or zero emission vehicles to exceed power unit (tractor) weight limits by up to 907 kg (2,000 lbs).[51] In Arizona, heavy-duty vehicles powered by electricity or hydrogen may also exceed weight limits by up to 907 kg (2,000 lbs).[52] In Canada, British Columbia announced in 2021, the allowance of an additional

Table 4: Canada and U.S. Vehicle Weight Regulations

Country	Type	Weight allowance
Canada	Tractor semitrailer (six axles)	46,500 kg (102,500 lbs)
	A train double (seven or eight axles)	53,500 kg (117,950 lbs)
	B train double (eight axles)	62,500 kg (137,800 lbs)
	C train double (eight axles)	58,500 kg (128,970 lbs)
	Straight truck (three axles)	24,250 kg (53,460 lbs)
	Truck – pony trailer (six axles)	42,250 kg (93,145 lbs)
	Truck – full trailer (seven axles)	53,500 kg (117,950 lbs)
U.S.	5-axle tractor semi-trailer (interstate and NHS limits)	36,300 kg (80,000 lbs)
	7-axle tractor twin-trailer	

Source: Adapted from National Academies of Sciences, Engineering, and Medicine [50]

48 Transportation Research Board (2010). Review of Canadian Experience with the Regulation of Large Commercial Motor Vehicles. Retrieved from: https://nap.nationalacademies.org/read/14458/chapter/11#92

49 The Council of Ministers Responsible for Transportation and Highway Safety (2019), Heavy Truck Weight and Dimension Limits for Interprovincial Operations in Canada. Retrieved from:https://comt.ca/english/programs/trucking/MOU%202019.pdf#page=8

50 National Academies of Sciences, Engineering, and Medicine, (2020). Reducing the Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: Final Report. Washington, DC: The National Academies Press. Retrieved from: https://doi.org/10.17226/25542

51 California, S. of. (2019). Near-zero-emission and zero-emission vehicles. Retrieved from: https://dot.ca.gov/programs/traffic-operations/legal-truck-access/ex-zero-emission-vehicle

52 U.S. Department of Energy (2016), Idle Reduction and Alternative Fuel Vehicle Weight Exemption. Retrieved from: https://afdc.energy.gov/laws/6559

1,500 kg (3,307 lbs) to electric full sized commercial vehicles and 1,000 kg (2205 lbs) to hydrogen powered trucks. [53] Overseas, in July 2023, the European Commission proposed the Weights and Dimensions Directive 96/53/EC (WDD) to increase weight limits for ZEHDVs from 42 to 44 tonnes to facilitate the adoption of cleaner technologies.[54] The allowance of additional truck weight could place an additional burden on infrastructure such as pavement and bridges, requiring more frequent maintenance and potentially resulting in higher costs and emissions.

3.1.4 Sales Mandates

North America

Sales requirement regulations for heavy-duty zero-emission vehicles (HDZEV) first started in California in 2021 with the *Advanced Clean Trucks (ACT) Rule*, the most advanced of its kind in North America. This rule requires manufacturers to sell between 5-9% of zero-emission heavy-duty vehicles (HDVs) starting in 2024, depending on the vehicle class. The required percentage gradually increases over time, reaching 30-50% by 2030, and 75% for Class 8 rigid trucks and 40% for Class 8 tractor trucks by 2035. More recently, in April 2023, California approved the world's first regulation to phase out the use of traditional combustion trucks the rule, known as Advanced Clean Fleets (ACF), is aligned with the state's long-term goal to transition to 100% zero emission MHD trucks in California by 2045. The ACF rule mandates that fleet operators gradually adopt zero-emission vehicles and is designed to complement the ACT Rule. [55] A summary table of ACF requirements can be found in Appendix B.

Following California's ACT policy, seventeen states to date[56] and the District of Columbia have signed an MOU to adopt the ACT mandate, requiring MHDV manufacturers to sell increasing share of zero emission trucks. The pledge has two main goals:

- Eliminate diesel MHDV sales by 2050 with an interim target of at least 30% of new MHD sales being ZEVs by 2030, and
- The signatories of the MOU must join forces to collaboratively work in the *Multi-State ZEV Task Force*.

In September 2021, the Government of Québec joined the Task Force. In July 2022, the Task Force created an action plan to accelerate the decarbonization of the heavy-duty sector and ensure that the MHD ZEV deployment also generates benefits to disadvantaged communities.[57] British Columbia is planning to create a sales mandate for MHDVs in alignment with California's ACT Rule, as part of the commitment described in the *CleanBC Roadmap to 2030*.[58]

Global

In 2021, at COP26, Canada became a signatory of the *Global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles (Global MOU)*. To date, the initiative has over 30 signatory countries with the goal to foster growth of the zero-emission medium- and heavy-duty vehicles sector.[59] The group has committed to 30% zero emission MHDV sales by 2030; and 100% by 2040.[60] The U.S. became a signatory of the MOU later at COP27 in 2022.

Further detail and a summary of sales and manufacturing regulations in California, U.S. and Canada are provided in Appendix B.

3.1.5 Financial Incentives

To foster the adoption of zero emission HDV, governments provide incentives to lower the initial investment burden. Most commonly, federal incentives are allocated to municipal budgets through zero emission funds.

53 British Columbia Government News (2021). Weight allowance greenlit for low-carbon commercial vehicles. Retrieved from: https://news.gov.bc.ca/releases/2021TRAN0035-000920

54 European Commission (2023), Questions and Answers on Weights and Dimensions: new proposal to accelerate the uptake of zero-emission heavy-duty vehicles and promote intermodal transport. Retrieved from: https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_3770

55 CARB (2023), TruckStop Resources, Retrieved from: https://ww2.arb.ca.gov/our-work/programs/truckstop-resources/zev-truckstop/regulations

56 California, Colorado, Connecticut, Hawaii, Maine, Maryland, Massachusetts, Nevada, New Jersey, New York, North Carolina, Oregon, Pennsylvania, Rhode Island, Vermont, Virginia, and Washington.

57 U.S. Department of Energy (2023), Medium- and Heavy-Duty (MHD) Zero Emission Vehicle (ZEV) Deployment Support. Retrieved from: https://afdc.energy.gov/laws/12460

58 Government of British Columbia (2023), Zero-Emission Vehicles Act. Retrieved from: https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/clean-transportation-policies-programs/zero-emission-vehicles-act

59 Calstar (2023), Global Memorandum of Understanding (MOU) on Zero-Emission Medium- and Heavy-Duty Vehicles. Retrieved from: https://globaldrivetozero.org/mou-nations/

60 Electric Autonomy (2021), Canada signs global agreement targeting 100 percent zero-emission truck and bus sales by 2040. Retrieved from: https://electricautonomy.ca/2021/11/09/cop26-zero-emission-truck-bus-canada/

Initially, funding was predominantly tailored to more easily electrifiable vehicles with predictable drive cycles and therefore predictable charging schedules such as transit buses. As zero emission Class 8 vehicles develop further, investments are targeting these vehicles.

Table 5 presents a high-level summary of incentive programs to fund the adoption of zero emission vehicles, including Class 8 long-haul trucks. Further details of each program, including full references, can be found in Appendix C.

"Modification of regulations to expand weight allowances for commercial vehicles will be crucial to foster ZEV technologies, primarily to compensate extra weight for the technologies in the short-term."

Table 5: Summary of Canadian HDV Funding Programs

Program Name	Funder	Eligible Activities	Total Fund
Incentives for Medium- and Heavy-Duty Zero-Emission Vehicles (iMHZEV) Program	Transport Canada	Purchase or lease of eligible MHZEVs	$547.5M
Zero Emission Vehicle Infrastructure Program (ZEVIP)	Natural Resources Canada	EV and hydrogen chargers in public places, on-street, inmulti-unit residential buildings, at workplaces, and for vehicle fleets	$680M
Programme Écocamionnage	QC Ministère des Transports et de la Mobilité Durable	Purchase of new electric or fuel cell trucks; purchase of used heavy vehicles and collaborative electric delivery projects	$86.5M[61]
Go Electric Rebates	BC Ministry of Energy, Mines and Low Carbon Innovation	Purchase of battery electric or hydrogen FC heavy-duty transport trucks, medium and heavy-duty trucks	$288M (for all vehicles)[62]
Commercial Vehicle Innovation Challenge (CVIC)	BC Ministry of Energy, Mines and Low Carbon Innovation	Development, demonstration, or commercialization of commercial ZEV product or technology	$30M
Commercial Vehicle Pilots Program (CVP)	BC Ministry of Energy, Mines and Low Carbon Innovation	Deployment of ZEV technology in commercial applications and supporting infrastructure	$89M[63]
Electrify Nova Scotia MHZEV Rebate Program	Department of Natural Resources and Renewables	Eligible vehicles encompass those in the federal iMHZEV incentive program (Class 2 to 8) [64]	$0.5M

61 Gouvernement du Quebec (2024). Programme Écocamionnage 2.0 – Après les voitures, Québec s'attaque à l'électrification des camions. Retrieved from: https://www.quebec.ca/nouvelles/actualites/details/programme-ecocamionnage-20-apres-les-voitures-quebec-sattaque-a-lelectrification-des-camions-37781

62 Government of British Columbia (2024). Go Electric Program. Retrieved from: https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/clean-transportation-policies-programs/clean-energy-vehicle-program

63 Government of BC (2023). B.C. drives industry shift to cleaner heavy-duty transportation. Retrieved from: https://news.gov.bc.ca/releases/2023EMLI0021-000600

64 EVAssist (2024). Electrify Rebates for Medium and Heavy-duty Zero Emission Vehicles (2024). Retrieved from: https://evassist.ca/rebates/mhzev/

3.2 Commercial Availability

Globally, zero emission vehicle model availability has been expanding, particularly in the MHD trucks segment. At the time of this report, model availability has increased by approximately 41% since 2021, mainly due to a rise in the number of HD trucks (116%), followed by cargo vans (71%) and MD trucks (59%) as illustrated in Figure 9.[65] HDV producers are progressively gaining the expertise to deliver larger, heavier zero emission vehicles with greater payloads. Similarly, the number of OEMs offering zero emission heavy-duty vehicles has increased in the past three years (Figure 10).[66]

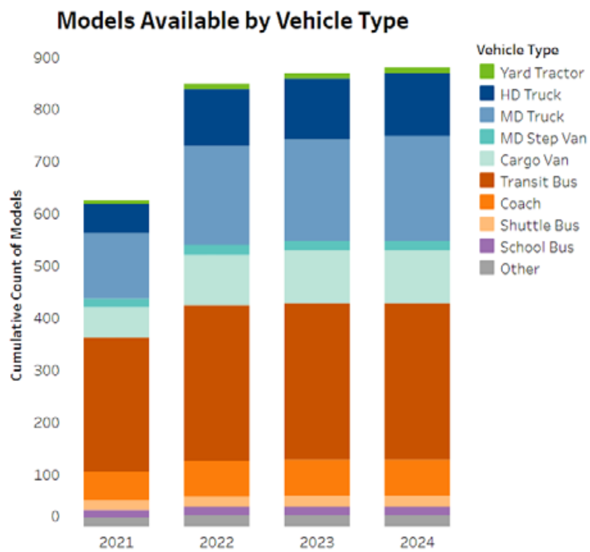


Figure 9: Global ZE-MDHV Model Availability (2021 to 2024)

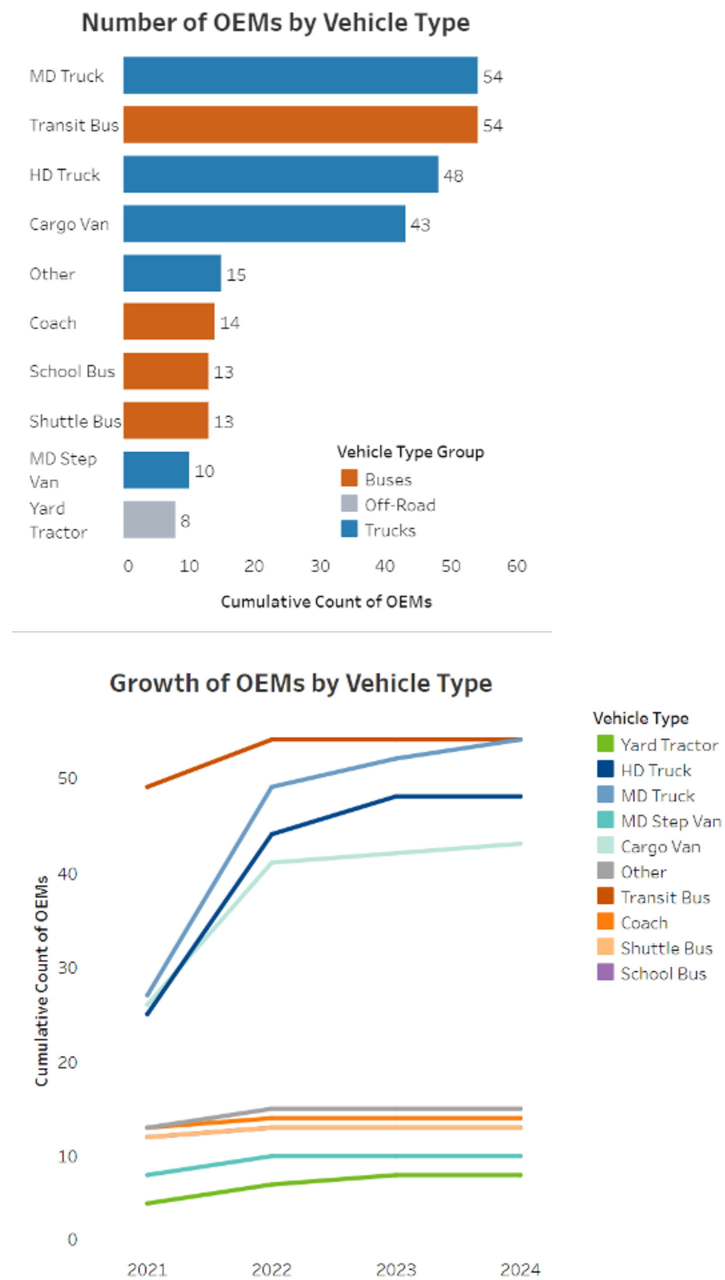


Figure 10: Global OEMs offering ZEVs by vehicle type

65 CALSTART (2024): Drive to Zero's Zero-Emission Technology Inventory Data Explorer. Version 3.5. Last updated November 2023. Retrieved from: https://globaldrivetozero.org/tools/zeti-data-explorer/

66 CALSTART (2024): Drive to Zero's Zero-Emission Technology Inventory Data Explorer. Version 3.5. Last updated November 2023. Retrieved from: https://globaldrivetozero.org/tools/zeti-data-explorer/

3.2.1 Current Class 8 Model Availability

Canada and U.S. follow the same global trends with respect to MHDVs. The number of heavy-duty truck (Class 7 and 8) models in Canada and the U.S. increased from 15 to 32 (a 113% increase) from 2021 to 2024, and the number of OEMs offering HD trucks increased from 8 to 19 (a 138% increase). [67]

Table 6 presents the model availability of heavy-duty zero emission Class 8 trucks in Canada and the U.S.[68] As described in Section 2.2.1, a number of these models are mainly viable for regional haul trucking at this stage. Note that some models may not yet be available in Canada.

Table 6 Top HD Truck OEMs by Range in Canada and US

OEM	Model	Type	Max Range (km)	Energy Capacity
Freightliner	eCascadia[69]	BEV	370 *	438 kWh
XOS	HDXT	BEV	370 *	N/A
Lion	Lion8T Tractor Truck	BEV	400 *	653 kWh
Volvo	VNR Electric	BEV	443 *	565 kWh
BYD	8TT ERR	BEV	485 *	563 kWh
Nikola	Tre BEV [70]	BEV	530 *	753 kWh
Einride	Truck	BEV	640 *	N/A
Tesla	Semi	BEV	800	1,000 kWh
Cenntro Electric Group	LM864H	FCEV	300 *	65.2kg
Toyota	Beta	FCEV	483 *	40 kg
Hyzon	HyHD8-200[71]	FCEV	560 *	50 kg
Kenworth	T680[72]	FCEV	725	58.8 kg
Hyundai	XCient Fuel Cell Tractor [73]	FCEV	725	68.6 kg
Nikola	Tre FCEV [74]	FCEV	800	70 kg
International	HD Hydrogen Fuel Cell Truck	FCEV	805	N/A

* : suitable for regional haul, based on limited range

3.2.2 Current Zero Emission HD Truck R&D Activities

Vehicle Developments

While the number of OEMs and models coming online in Canada and the U.S. has been steadily increasing, Class 8 BEV and FCEV trucks are still in the early stages of commercialization. Commercial activity in the HDV electrification sector has surged with dozens of manufacturers making significant investments to bring ZEVs to market.[75] FCEV trucks technology development is also evolving, with the establishment of the U.S. based Million Mile Fuel Cell Truck Consortium (M2FCT) supporting opportunities for fuel cell adoption in the HDV market through research and development (R&D). The M2FCT initiative focuses on four pillars: materials development, component integration, component and fuel cell durability, and system analysis. [76]

A number of both battery electric and hydrogen fuel cell trucks are being tested in real-world operations through partnerships between OEMs, governmental agencies, and industry organizations. For example, Transport Canada's Zero Emission Trucking Program has launched three Zero Emission Trucking TestBeds to evaluate the performance of Class 8 battery-electric and hydrogen fuel cell trucks in Canadian commercial freight operations across diverse locations, terrains and climates. Together, these deployments will amass over 500,000 kilometers of zero emission trucking data and user experiences on the performance of zero-emission freight-hauling trucks and their cost of operation compared to diesel equivalents.

67 CALSTART (2024): Drive to Zero's Zero-Emission Technology Inventory Data Explorer. Version 3.5. Last updated November 2023. Retrieved from: https://globaldrivetozero.org/tools/zeti-data-explorer/

68 CALSTART (2024): Drive to Zero's Zero-Emission Technology Inventory Data Explorer. Version 3.5. Last updated November 2023. Retrieved from: https://globaldrivetozero.org/tools/zeti-data-explorer/

69 Freightliner, Electric, eCascadia. Retrieved from: https://www.freightliner.com/trucks/ecascadia/

70 Nikola, TRE BEV. Retrieved from: https://www.nikolamotor.com/the-nikola-tre-bev-reinventing-short-haul-transportation/

71 Hyzon, Vehicles. Retrieved from: https://www.hyzonfuelcell.com/vehicles/hyhd8-200kw

72 Kenworth, T680 Fuel Cell Electric Vehicle. Retrieved from: https://www.kenworth.com/trucks/t680-fcev/

73 Hyundai, XCIENT Fuel Cell Tractor. Retrieved from: https://ecv.hyundai.com/global/en/products/xcient-fuel-cell-tractor-fcev

74 Nikola, Hydrogen Fuel Cell EV. Retrieved from: https://nikolamotor.com/tre-fcev/

75 International Council on Clean Transportation, Environmental Defense Fund, Propulsion Quebec Race to Zero (2020). How manufacturers are positioned for zero emission commercial trucks and buses in North America. Retrieved from: https://theicct.org/publication/race-to-zero-how-manufacturers-are-positioned-for-zero-emission-commercial-trucks-and-buses-in-north-america/

76 Oak Ridge National Laboratory (2021). Heavy duty vehicles an ideal entry into hydrogen fuel cell use. Retrieved from: https://www.ornl.gov/news/heavy-duty-vehicles-ideal-entry-hydrogen-fuel-cell-use

As part of the Testbeds, FCEV demonstrations are taking place in Alberta with the testing of a number of models. The Alberta Zero Emissions Truck Electrification Collaboration (AZETEC) initiative will see the deployment of two long-range (700 km) FCEV trucks between Edmonton and Calgary, commencing in 2024. Earlier tests from 2023 have focused on the testing of an FCEV model over shorter distances to accommodate a lack of appropriate fueling infrastructure.[77]

On the BEV front, Tesla tested their Class 8 Semi in December 2022, completing an 800 km journey in mountainous terrain fully loaded at 37,195 kg (82,000 lb) in the U.S.[78] While this represents a significant milestone, concerns persist about scalability for long-haul trucking. The test used a trailer tractor combination with excellent aerodynamics, not representative of all real-world applications. Moreover, the battery was drained completely, contrary to OEM recommendations for longevity. In Canada, a number of companies have acquired and are testing a small number of Class 8 trucks for regional return-to-depot operations with shorter daily distances than long-haul operations.[79]

Supply Chain Developments

Battery Electric

In recent years, Canada has witnessed a significant evolution in its battery electric supply chain, particularly for heavy-duty vehicles. When it comes to the potential to develop a secure, reliable and sustainable battery supply chain, Canada is positioned as the leader, surpassing China for the first time, according to BloombergNEF's Global Lithium-Ion Battery Supply Chain Ranking.[80] Canada's potential stems from its continuous progress in manufacturing and production, robust ESG credentials, deep integration with the U.S. economy, and unwavering policy commitment at both provincial and federal levels. Other factors play an important role in Canada's battery supply chain, such as the abundance of critical minerals, leading battery research and innovation, and a mature manufacturing ecosystem.[81]

The main electric MHDV production clusters in Canada are located in Quebec and Manitoba. Manitoba's cluster is focused on buses while Quebec is specialized in trucks and buses.[82] With companies like Lion Electric leading the way, Quebec has become a significant hub for heavy-duty trucks. In 2023, Lion Electric, a leader in the segment, inaugurated its lithium-ion batteries manufacturing unit for MHDV. The facility will enable the electrification of approximately 14,000 MHDV per year. [83]

Hydrogen

Canadian companies working in the hydrogen sector cover all aspects of the hydrogen fuel cell vehicle supply chain – from hydrogen production and distribution, to refueling stations, to the actual manufacture of the vehicles. The sector's most notable cluster is in British Colombia, but other clusters exist in Ontario, Quebec and Alberta.

The hydrogen powertrain solutions developed by Vancouver's Ballard power have been deployed in commercial vehicles globally since 1990. Over the past decade, its fuel cell system has been used in transit buses in over 15 countries.[84] Ballard has created a cluster of fuel cell expertise and enabled Cellcentric, a joint venture between Daimler Truck AG and the Volvo Group, to install its first Canadian operations in Burnaby, B.C. With 70 employees, the centre is producing components for next-generation fuel cell systems to power heavy-duty trucks.[85]

Canada is supporting the supply chain through programs such as Canada's Strategic Innovation Fund, which is investing in several innovative vehicle manufacturing plants to promote ZEVs and allow Canada to play a role in the future green economy.

77 Electric Autonomy Canada (2023). Class 8 hydrogen truck demo lets Alberta carriers conduct real-world test drives. Retrieved from: https://electricautonomy.ca/2023/08/16/hydrogen-truck-demo-alberta-carriers/

78 Motortrend (2022). The Tesla Semi Truck Is Finally Here After Years of Waiting—Can It Haul the Expectations?. Retrieved from: https://www.motortrend.com/news/2023-tesla-semi-truck-ev-first-look-review/

79 Newswire (2023). Loblaw rolls out first battery electric transport truck, a major milestone toward its goal of a carbon-neutral fleet. Retrieved from: https://www.newswire.ca/news-releases/loblaw-rolls-out-first-battery-electric-transport-truck-a-major-milestone-toward-its-goal-of-a-carbon-neutral-fleet-807069561.html

80 BloombergNEF (2024). China Drops to Second in BloombergNEF's Global Lithium-Ion Battery Supply Chain Ranking as Canada Comes Out on Top. Retrieved from: https://about.bnef.com/blog/china-drops-to-second-in-bloombergnefs-global-lithium-ion-battery-supply-chain-ranking-as-canada-comes-out-on-top/

81 Clean Energy Canada (2022), Canada's New Economic Engine. Modelling Canada's EV battery supply chain potential—and how best to seize it. Retrieved from: https://cleanenergycanada.org/wp-content/uploads/2022/09/CanadasNewEconomicEngine_Web.pdf

82 International Council on Clean Transportation (2020), Canada's Role in the Electric Vehicle Transition, Retrieved from: https://theicct.org/publication/canadas-role-in-the-electric-vehicle-transition/

83 Cision (2023), Lion Electric inaugurates its battery manufacturing factory for medium and heavy-duty vehicles. Retrieved from: https://www.newswire.ca/news-releases/lion-electric-inaugurates-its-battery-manufacturing-factory-for-medium-and-heavy-duty-vehicles-879357548.html

84 International Council on Clean Transportation (2020), Canada's Role in the Electric Vehicle Transition, Retrieved from: https://theicct.org/publication/canadas-role-in-the-electric-vehicle-transition/

85 Electric Autonomy (2023), B.C. fuel cell expertise is driving growth for a Daimler Trucks-Volvo Group joint venture. Retrieved from: https://electricautonomy.ca/2023/03/02/fuel-cell-daimler-volvo-cellcentric/

3.3 Total Cost of Ownership

3.3.1 Battery Electric Economics

The capital costs of BEV long-haul trucks are limited to the cost of the vehicles themselves. It is assumed that the cost of fast charging infrastructure will be incurred by charging station operators and potentially electrical utilities across long-haul corridors, who will then transfer these capital and station maintenance costs through charging fees. Appendix D presents the estimated capital upgrade costs in the U.S. for a large-scale charging hub, not including the costs of higher power (1000-3750 kW) MCS chargers that are still not currently commercially available.

Electric vehicle batteries have experienced significant price decreases over the past decade, and this trend is expected to continue. Consequently, the adoption of this technology in the MHDV sector has been growing, particularly among early adopters and on a small scale that does not necessitate significant infrastructure upgrades. This trend is especially notable in regions offering financial incentives.

Reductions in battery costs improve the economics of long-haul trucks. However, the range requirements of long-haul trucking entail very large batteries, resulting in a significant price differential relative to diesel vehicles. OEMs have not yet released Class 8 vehicles capable of long-haul trucking (with the exception of the Tesla model that has a larger 1,000 kWh battery). Studies show an expected price differential of around $350,000[86] for 1,000 kWh Class 8 long-haul trucks, which have larger batteries than the existing regional Class 8 trucks with an average battery size of 450 kWh.[87] Overall, the capital cost of long-haul trucks will depend on battery sizes included in the trucks, which will be dependent on charging speed capacity on freight corridors. Current Class 8 trucks, averaging a range of up to 350 km, could adapt to a model that utilizes megawatt fast chargers if drivers are prepared for more frequent charging stops than usual. However, this approach incurs extra costs due to the additional waiting time at charging stops. Furthermore, the existing technology's payload limitations may require trucking companies to use more vehicles than currently, especially for loads exceeding U.S. weight limits.

"Overall, the capital cost of long-haul trucks will depend on battery sizes included in the trucks, which will be dependent on charging speed capacity on freight corridors."

The economics of electric vehicles generally involve higher upfront costs, followed by operational savings from maintenance and charging over the vehicle's lifetime. While charging costs are expected to be lower than diesel costs, they are still uncertain at this stage due to the evolving development of megawatt chargers with uncertain pricing, as well as the cost of grid upgrades that will have to be incurred by charging station operators or utilities. Maintenance costs of battery electric trucks are expected to be lower than diesel trucks at maturity due to the significantly lower number of total parts in the vehicle. However, the early prototypes to be tested will not reveal maintenance data representative of production-level vehicles. Gradual deployments, in parallel with volume production and technology iterations, will allow the technology to mature over time. Additionally, it is unclear at this early stage whether the use of megawatt charging will impact battery degradation, potentially requiring faster replacement of batteries throughout a vehicle's lifecycle.

Early adopters of the technology will require financial support to overcome the hurdles of first-generation technologies. Studies conducted in the North American context predict long-haul battery electric trucks to reach cost parity with diesel between 2027 and 2036.[88]

86 Converted from USD to CAD at a rate of 1.34

87 ICCT (2023). Total cost of ownership of alternative powertrain technologies for Class 8 Long-Haul trucks in the US. Retrieved from: https://theicct.org/publication/tco-alt-powertrain-long-haul-trucks-us-apr23/

88 RMI (2022). Making Zero Emission Trucking Possible. Retrieved from: https://missionpossiblepartnership.org/wp-content/uploads/2022/11/Making-Zero-Emissions-Trucking-Possible.pdf

89 Converted from USD to CAD at a rate of 1.34

90 ICCT (2023). Total cost of ownership of alternative powertrain technologies for Class 8 Long-Haul trucks in the US. Retrieved from: https://theicct.org/publication/tco-alt-powertrain-long-haul-trucks-us-apr23/

3.3.2 Hydrogen Fuel Cell Economics

Similarly to battery electric long-haul trucks, hydrogen fuel cell long-haul trucks' capital expenses include the vehicle itself. It is assumed that fueling infrastructure would be provided through fueling providers at refueling hubs, with the cost of hydrogen refueling infrastructure deployment and maintenance translated into the cost of fueling at the pump. Long-haul hydrogen fuel cell trucks are significantly more expensive than diesel trucks, with estimates indicating a difference of around $600,000[89] in the costs of the trucks.[90] Cost reductions are expected in all components of hydrogen fuel cell trucks over time as production capacity grows. In low-volume production, using standard automotive parts in heavy-duty trucks can result in compromises due to the parts not being tailored for heavy-duty applications. The U.S. Department of Energy outlines goals for reducing the cost of different components in hydrogen fuel cell trucks, including the fuel cell and the on-board hydrogen storage.[91] Moreover, akin to the challenges faced by battery electric trucks, payload limitations of current hydrogen technology could compel trucking companies to deploy additional vehicles for carrying loads that exceed U.S. weight regulations.

Hydrogen fuel cell maintenance costs are expected to be lower than diesel trucks similar to battery electric trucks.[92] Hydrogen costs at the pump will vary significantly based on the method used to produce hydrogen and the hydrogen distribution network, with green hydrogen being twice as expensive. Studies show that hydrogen needs to reach between $4/kg and $8/kg[93] for it to compete with diesel vehicles within the next decade from a cost-effectiveness perspective.[94] The volume of vehicles and demand necessary to achieve the scale required for cost competitiveness with diesel is unlikely to be attained solely through commercial truck transportation. As a result, subsidized hydrogen is expected to be essential for an extended period, and suboptimal choices in hydrogen supply, such as grey hydrogen produced from natural gas, which is more likely to achieve commercially viable price points in the short and medium term, may be necessary for decades. There is also a lack of clarity on whether the green hydrogen produced in Canada will be allocated to trucking or other hydrogen-consuming sectors first.

There is room for improvements in green hydrogen production at scale through R&D. The current environmental outlook is positive with the Inflation Reduction Act (IRA) in the U.S. and various programs put in place in Canada.[95] The details of the Canadian Clean Hydrogen Investment Tax Credit (ITC) were confirmed in the 2023 federal budget. This refundable investment tax credit applies to clean hydrogen projects, providing support ranging from 15 to 40 percent of eligible project costs. The level of support is higher for projects generating the cleanest hydrogen. Additionally, the Clean Hydrogen ITC extends a 15 percent tax credit to equipment essential for converting hydrogen into ammonia for transportation purposes. This tax credit is only applicable when ammonia production is associated with the production of clean hydrogen.[96]

91 NACFE (2023). Hydrogen trucks, long haul's future? Retrieved from: https://nacfe.org/research/electric-trucks/hydrogen/

92 At this early prototype stage, it is unclear whether the fuel cell and tanks will require additional maintenance.

93 Converted from USD at 1.34

94 ICCT (2023). Total cost of ownership of alternative powertrain technologies for Class 8 Long-Haul trucks in the US. Retrieved from: https://theicct.org/publication/tco-alt-powertrain-long-haul-trucks-us-apr23/

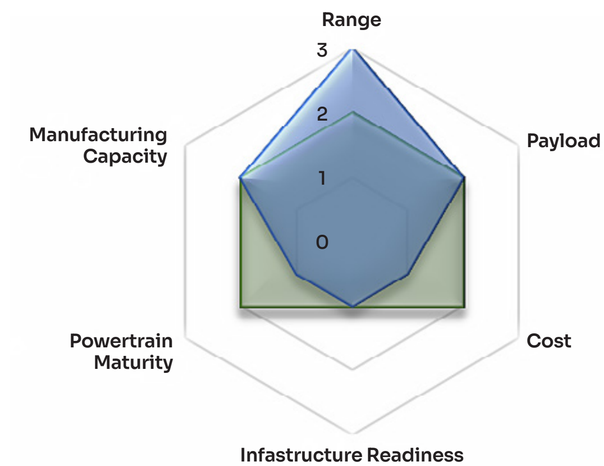
95 Hydrogen Council (2023). Hydrogen Insights 2023. An update on the state of the global hydrogen economy, with a deep dive into North America. Retrieved from: https://hydrogencouncil.com/wp-content/uploads/2023/05/Hydrogen-Insights-2023.pdf

96 Canadian Hydrogen and Fuel Cell Association (2023). Canada's hydrogen sector welcomes Budget 2023. Retrieved from: https://www.chfca.ca/2023/04/05/canadas-hydrogen-sector-welcomes-budget-2023/

4 Synthesis and Comparative Analysis

PHOTO: GETTY IMAGES/ MILOS-MULLER

The current prevailing technology for Class 8 long-haul is diesel ICE with an established ecosystem. For the purposes of this comparison, diesel ICE is considered as the operational benchmark. In other words, it is the incumbent technology for heavy-duty long-haul road transport that allows for sufficient payloads and range to be economical, and operates within a well-established ecosystem (e.g., fueling, O&M, etc.). Figure 11 present a visual representation of key factors comparing the technology and market readiness of battery electric and hydrogen fuel cell technologies to the operational benchmark. It indicates where each technology meets the current operational benchmark (3), is under development (2), or requires significant progress to meet the current operational benchmark (1). The radar chart presents the relative strengths and weaknesses of the two technologies. Overall, a larger area indicates proximity to the current operational benchmark.



Technology and Market Readiness Rank

Technology meets current benchmark	3
Technology is under development	2
Significant progress needed	1

- Battery Electric Powertrain
- Hydrogen Fuel Cell Powertrain

Figure 11 Technology and Market Readiness Overview

Technology and Market Readiness

Long-haul trucking operations represent a distinctive segment within the road freight sector, characterized by extensive travel distances and heavy payloads. As a result, assessing the viability of zero emission technologies for long-haul trucking hinges on operational capabilities such as range and payload. In 2024, planned production of hydrogen fuel cell Class 8 models reveals higher range capabilities compared to battery electric trucks. Commercially available battery electric Class 8 truck ranges are suitable primarily for regional hauls at this stage.

In terms of payload, the significant weight of batteries currently presents a major challenge for battery electric technology—a problem slightly less pronounced in hydrogen fuel cell trucks due to their lighter hydrogen storage. Although both technologies are expected to see weight reductions with increased production capacity, they are currently designed to meet U.S. trucking weight limits, which are lower than those in Canada. Adapting these technologies for the heaviest Canadian East/West long-haul applications will introduce additional range limitations due to the impact of heavier payloads on energy efficiency, potentially affecting their adoption rates in Canada.

Both technologies are in the early stages of development and show potential for improvement with continued R&D investments by OEMs. BEV trucks, for instance, could see advancements in battery energy density, transmission efficiency, and road load technologies, thereby overcoming existing range and weight limitations. Furthermore, the development of new battery chemistries could significantly enhance their operational capabilities over time.[97] Similarly, significant investments are underway to improve FCEV technology in the long-haul sector.

From a total cost of ownership perspective, the cost differential for FCEV trucks is higher than that of BEV trucks. Both options are significantly more expensive than diesel trucks at this stage and aim to benefit from economies of scale with higher production, contingent on technological breakthroughs and infrastructure investments. While both are expected to have lower maintenance costs than diesel, battery electric technology is expected to hold a slight advantage due to the lower number of total parts.

"Significant investments in distribution infrastructure for hydrogen and electricity are necessary, accompanied by advancements and testing of very high-power chargers and high-pressure hydrogen refueling stations. Progress is being made on all fronts, but the technology that attracts the most investment in specific freight corridors will likely play a crucial role in determining the direction of the industry."

Charging costs for battery electric trucks are also significantly lower than green hydrogen costs. However, charging and fueling costs will heavily depend on how infrastructure is developed and priced on long-haul corridors, creating a potential disconnect between production costs and costs at the charging stations or hydrogen pumps. Significant investments in distribution infrastructure for hydrogen and electricity are necessary, accompanied by advancements and testing of very high-power chargers and high-pressure hydrogen refueling stations. Progress is being made on all fronts, but the technology that attracts the most investment in specific freight corridors will likely play a crucial role in determining the direction of the industry.

Existing Class 8 BEVs being manufactured are currently mainly only suitable for regional haul trucking. However, Tesla aims to start volume production of a model designed for certain long-haul applications in 2024. Meanwhile, the manufacturing capacity for long-haul FCEV trucks remains limited. Nevertheless, several models suited for long-haul trucking are planned for release, primarily due to the more advanced readiness of hydrogen fuel cell technology in scenarios where refueling infrastructure has been addressed.

97 Energy Monitor (2023). US scientists make breakthrough for long-range EV batteries. Retrieved from: https://www.energymonitor.ai/transport/us-scientists-make-breakthrough-for-long-range-electric-vehicle-batteries/?cf-view

The regional haul applications of Class 8 BEVs have the potential to foster technological improvements which could support range increases for long-haul applications. Long haul FCEV trucks are already at the prototype stage, with the launch of the first-generation production models anticipated in 2024.

The development of charging and hydrogen refueling networks will require significant infrastructure investments and risk. It is possible that the long history of building electrical systems will be a benefit to developing a charging network but developing a charging network for long-haul transportation risks being constrained over capacity concerns in certain locations. Hydrogen may benefit from its more modular nature, in that a refueling system can start with one or two refueling points with hydrogen transported to the station by truck, and then expanding as demand increases. As such, it may be faster and more cost-effective to start a hydrogen network. However, at this stage there is insufficient information available to determine if building out the electrical system or developing a new hydrogen refueling network will be the most cost-effective option.

Trends in Regulations and Incentives

North American emissions regulations are becoming increasingly stringent, requiring significant advancements in the incumbent technologies (e.g., diesel ICE vehicles, before and after market emissions controls, etc.). This is expected to result in increasing production, capital, and operating costs for HDVs.

Despite the evolving regulations that support the development and implementation of zero emission HDVs, high prices continue to represent a significant barrier. Vehicle incentives and investment in infrastructure will be required for ZEV technologies to become economically feasible. Encouragingly, there has been a recent influx of financial support for the broader ecosystem for zero emission trucks, including R&D, pilot deployment/adoption, infrastructure, as well as supporting elements, such as guidelines, codes, and standards. A summary of key programs in this area was presented in Section 3.1.5 Financial Incentives.

Further to the regulations and incentives, there is increasing movement at the provincial/state and federal levels to mandate sales of ZEVs. These typically gradually increase to 100% zero emission MHDV new sales between 2035 and 2045 depending on location and vehicle type. The implications for smaller owner-operators in this transition are significant, as they tend to be more financially constrained and rely on the resale used vehicle market. They may require targeted support to ensure they can keep pace with industry changes.

5 Conclusion

PHOTO: GETTY IMAGES/ HISPANOLISTIC

Under the current model of North American long-haul freight transportation, Class 8 trucks are designed to travel with heavy loads over long distances, following strict operational regulations. They are an integral part of Canada's economy and also a significant contributor to the transport sector's GHG and CAC emissions. Efforts are underway to mitigate the impacts of emissions and decarbonize the on-road sector. Two primary pathways have been identified: BEVs and FCEVs. The relatively clean Canadian electricity grid is promising in terms of supporting decarbonization, enabling significant emissions reductions for both technologies.

Current ZEV models for both BEV and FCEV Class 8 trucks present range and payload limitations relative to diesel ICE vehicles. The existing ZEV models do, however, show potential for specific, less-than-full-truckload weight applications and both technologies show potential for improvement (toward full load long-haul applications) with continued R&D investments by OEMs. For example, advancements for BEVs may include increased battery energy density, new battery chemistries, and road load technologies. For hydrogen FCEVs, improvements should be focused on areas such as materials and fuel cell durability.

Financial incentives are likely to play a major role in the near future, facilitating the testing of these technologies under pilot conditions. Although the current application landscape is limited in Canada, plans for Class 8 long-haul FCEV pilots in Alberta are underway. Simultaneously, the deployment of BEV Class 8 regional haul applications is growing in Canada, with anticipation for technological advances that will enable long-haul applications in the future.

The success of both the current models and potential future BEV and FCEV technologies is contingent on the development of essential infrastructure (e.g., a widespread network of high-powered public charging stations for BEVs and a comprehensive national hydrogen distribution network for FCEVs). The realization of this potential hinges on a detailed assessment of charging or hydrogen fueling infrastructure needs, followed by the deployment of the infrastructure. For example, the power loads associated with long-haul charging infrastructure sector are very high and meeting these loads will require significant planning and be very costly to install. Similarly, green hydrogen production and hydrogen distribution infrastructure will require substantial investments to achieve viability.

Even though there is still much progress to be made, regulations are evolving to advance the viability of zero emission heavy duty trucks. At the same time, a number of financial programs have recently kicked off to support various aspects of the ZEV supply chain, including for development and deployment of battery electric and hydrogen fuel cell Class 8 long-haul trucks. To create cost breakthroughs that enable a more market driven trajectory to zero emissions, both governments and private financial institutions must direct capital to high priority research and development and small-scale deployments. Efforts should also be focused on unbottling renewables through new electricity generation and transmission, and hydrogen distribution capabilities.

"Current ZEV models for both BEV and FCEV Class 8 trucks present range and payload limitations relative to diesel ICE vehicles. The existing ZEV models do, however, show potential for specific, less-than-full-truckload weight applications and both technologies show potential for improvement (toward full load long-haul applications) with continued R&D investments by OEMs."

PHOTO: GETTY IMAGES/ VITPHO

Appendix A

GHG and CAC Emissions Regulations

GHG Emissions Regulations

Canada

In Canada, tailpipe emissions for HDVs and engines are regulated by ECCC under the *Canadian Environmental Protection Act, 1999* to limit GHG and CAC emissions. In 2013, Canada finalized the first phase of the *Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations*. In 2018, the regulations for on-road HDV were updated (Phase 2) and apply to MY 2021 and later. Phase 2 was last updated in October 2022. Similar to the U.S. Phase 2 GHG rulemaking (described below), Canada's second phase regulations added Class 8 trailers as a category for regulated emissions standards. However, in response to a legal challenge in the U.S., ECCC has issued multiple interim orders to suspend the enforcement of the trailer-related provisions in the Phase 2 regulation. [98]

United States

In September 2011, the EPA, in coordination with National Highway Traffic Safety Administration (NHTSA) issued the Phase 1: *Greenhouse Gas Rule for model years 2014-2018* for MHD vehicles. The standards are tailored to combination tractors, heavy-duty pickup trucks and vans, and vocational vehicles. In October 2016, the U.S. Phase 2 GHG rulemaking was released to set greenhouse gas limits for MHD vehicles for model years 2018-2027. This rule covers model years 2018-2027 for certain trailers and model years 2021-2027 for semi-trucks, large pickup trucks, vans, and all types and sizes of buses and work trucks.[99] On March 29, 2024, EPA issued a final rule: Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3.[100] Phase 3 revises the Phase 2 standards for MY 2027 and sets new, more stringent standards for MY 2028 – 2032. Phase 3, along with the 2022 EPA standards to control smog and soot air pollution from new heavy-duty engines and vehicles fulfill the intent of EPA's Clean Trucks Plan, as it relates to heavy-duty trucks.

Following the release of the more stringent Phase 3 in the U.S., ECCC is expected to initiate a review of Canadian emission standards in the upcoming years.

Differences between U.S. and Canada

The regulations in Canada have historically been aligned with the United States EPA national emissions standard, for medium- and heavy-duty vehicles. In respect of U.S. and Canada's HDV GHG emission regulation alignment, both are similar with regard to regulatory design, vehicle groupings, limit values, and timing. Nonetheless, it is important to highlight two key differences:[101]

- The U.S. standard is a joint fuel consumption and GHG emission standard, while in Canada the standard is related to GHG emissions only.
- Any EPA certified engine may be sold in Canada without demonstrating compliance with Canada sales-weighted averaging, as long as determined sales thresholds are met.

98 Government of Canada (2024), Canada Gazette, Part I, Volume 158, Number 11: ORDERS IN COUNCIL. Retrieved from: https://www.gazette.gc.ca/rp-pr/p1/2024/2024-03-16/html/order-decret-eng.html

99 EPA (2024), EPA Emission Standards for Heavy-Duty Highway Engines and Vehicles. Retrieved from: https://www.epa.gov/emission-standards-reference-guide/epa-emission-standards-heavy-duty-highway-engines-and-vehicles

100 Environmental Protection Agency. 40 CFR Parts 86, 1036, 1037, 1039, 1054, and 1065. Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3. Retrieved from: https://www.epa.gov/system/files/documents/2024-03/hd-phase3-veh-standrds-ghg-emission-frm-2024-03.pdf

101 Transport Policy (2018), Canada: Heavy-Duty: GHG. Retrieved from: https://www.transportpolicy.net/standard/canada-heavy-duty-ghg/

102 Government of Canada. On-Road Vehicle and Engine Emission Regulations (SOR/2003-2). Current as of March 20, 2024. Last amended October 3, 2022. Retrieved from: https://laws-lois.justice.gc.ca/eng/regulations/sor-2003-2/index.html

CAC Emissions Regulations

Canada

Canada's current CAC emission standard for HDVs, the On-Road Vehicle and Engine Emission Regulations (Phase 2), was published in 2003, coming into effect in 2004 and last amended in October 2022.[102] For heavy-duty engines, the regulation aligns with (and refers to) Sections 10 and 11 of Title 40, chapter I, subchapter C, part 86, subpart A of the CFR. Canada's engine emission standard by engine type is presented in Table A.3.

Table A.3 – Heavy-Duty Engine (HDE) Emission Standards (g/bhp-hr)

MY	Engine type	GVWR kg (lb)	NOx	NMHC	NOx + NMHC	CO	PM
2005-2020	Otto HDE[103]	> 6,350 (14,000)	—	—	1.0	37.1 –	—
2007+	Diesel HDE	≥ 3,856 (8,500)	0.2	0.14	—	15.5 (compression-ignition) 14.4 (spark-ignition)	0.01

United States

On December 20, 2022, EPA adopted the final rule for Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards.[104] The summary of current U.S. exhaust emission standards is presented in Table A.4.

Table A.4: U.S. HDE Emission Standards (g/bhp-hr)

MY	Engine type	GVWR kg (lb)	NOx	NMHC	NOx + NMHC	CO	PM
2026 & earlier	Spark-ignition HDE; Compression-ignition	> 6,350 (14,000)	0.2	0.14	—	15.5 (compression-ignition) 14.4 (spark-ignition)	0.01
2027+	Spark -ignition HDE	> 6,350 (14,000)	0.035	0.06	—	6	0.005

According to the EPA, by 2045 emissions from heavy-duty highway vehicles are expected to be reduced by 48% for NOx, 8% for primary $PM_{2.5}$, 23% for VOC, and 18% for CO[105] as a result of this new Rule. Following the U.S.'s lead, Canada is expected to update its regulations to restrict CAC emissions from heavy-duty vehicles starting in MY 2027.

Differences between U.S. and Canada

Similar to the GHG emissions regulations alignment between U.S and Canada, CAC emissions regulations are also currently aligned for MY 2026 and earlier. The main difference between Canada's *On-Road Vehicle and Engine Emission Regulations (Phase 2)* and U.S.'s legislation is the phase-in period. However, this has only a small impact since Canada recognizes U.S. EPA emission certificates.[106] Under Canadian regulation, companies can choose between complying with EPA emission certification and in-use standards referred to in the EPA certificate or to the *On-Road Vehicle and Engine Emission Regulations*.

105 United States Environmental Protection Agency (2022), Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards. Retrieved from: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1016A9N.pdf

106 EPA emission certificates means a certificate of conformity to U.S. federal standards issued by the EPA. The Clean Air Act requires that all engines and vehicles be covered by a certificate of conformity before they can enter into commerce. A certificate of conformity demonstrates that the respective engine or vehicle conforms to all of the applicable emission requirements.

Appendix B
Sales Mandates

North American and global sales mandates related to zero emission vehicles were presented in Section 3.1.4. Additional details of the April 2023 rule, known as *Advanced Clean Fleets (ACF)*, for California is presented below. In addition, a summary table of sales and manufacturing regulations in California, U.S. and Canada is provided at the end of this appendix.

ACF is designed to complement the ACT Rule, as it mandates manufacturers to sell only zero emission MHD vehicles starting in 2036, as well as sets requirements for three types of fleets: (a) *drayage trucks at California's ports*, (b) *state and local government fleets*, (c) *high priority fleets* with vehicles that are suitable for electrification, their subhaulers, and entities that hire them.[107] Below is a summary table of the different components of ACF's three main groups, their application, affected vehicles and requirements (Table B.2). Acknowledging the challenges of ZEV adoption, CARB gives the option to *state and local government fleets, and high priority and federal fleets* to choose the ZEV milestone option which sets gradual zero emission fleet percentage of vehicles that must be zero emission. This option provides more flexibility and recognizes the different stages of technology and market readiness for three different groups of fleets (Table B.1).

Table B.1 Summary of ACF Groups [108]

Group	Applies to:	Affected vehicles:	Requirements
High Priority & Federal Fleets	▪ Fleets with 50+ vehicles, including common ownership and control ▪ Fleets with greater than $50 million in revenue ▪ Federal government fleets ▪ Entities that hire or dispatch fleets	▪ Class 2b-8 on-road vehicles ▪ Off-road yard tractors ▪ Light-duty package delivery vehicles	Fleets may elect between Model Year Schedule requirement or ZEV **Milestones Option** ▪ ***Model Year Schedule:*** Beginning 2024: fleets must purchase only ZEVs. Starting January 1, 2025: internal combustion engine vehicles must be removed at the end of their useful life as specified in the regulation. ▪ ***ZEV Milestones Option:*** described per Table B.2
State & Local Government	▪ State and local government agencies that own, lease, or operate MDHD trucks* *Agencies in designated counties and divisions with 10 or fewer trucks are exempt until 2027	All MDHD trucks	Fleets may elect between Zero Emission Purchase requirements or ZEV Milestones Option: ▪ ***Zero Emission Purchase requirements:*** Starting in 2024: 50% of purchases must be zero emission. Starting 2027: 100% purchases must be zero emission. ▪ ***ZEV Milestones Option:*** described per Table 8

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107 CARB (2023), TruckStop Resources. Retrieved from: https://ww2.arb.ca.gov/our-work/programs/truckstop-resources/zev-truckstop/regulations

108 The success of both the current models and potential future battery electric and fuel cell technologies is contingent on the development of essential infrastructure (e.g., a widespread network of high-powered public charging stations for BEVs and a comprehensive national hydrogen distribution network for FCEVs). The realization of this potential hinges on a detailed assessment of charging or hydrogen fueling infrastructure needs, followed by the deployment of the infrastructure. For example, the power loads associated with long-haul charging infrastructure sector are very high and meeting these loads will require significant planning and be very costly to install. Similarly, green hydrogen production and hydrogen distribution infrastructure will require substantial investments to achieve viability.

Even though there is still much progress to be made, regulations are evolving to advance the viability of zero emission heavy duty trucks. At the same time, a number of financial programs have recently kicked off to support various aspects of the zero emission vehicle supply chain, including for development and deployment of battery electric and hydrogen fuel cell Class 8 long-haul trucks.

Group	Applies to:	Requirements
Drayage fleets	▪ Class 7-8 on-road trucks operating at California's seaports and intermodal railyards	▪ Starting in 2024: Buy only ZEV drayage trucks, ▪ By 2025: Report the mileage of trucks more than 12 years old, ▪ By 2035: Ensure that 100% fleet trucks are ZEVs, regardless of vehicle age or operating miles traveled, ▪ Remove a truck from the system if it reaches the earlier of 18 years or 800,000 miles, or a minimum of 13 years if the truck has more than 800,000 miles.

Table B.2 ZEV Fleet Milestone by Milestone Group and Year [109]

Zero emission Fleet Percentage of vehicles that must be ZE	10%	20%	50%	75%	100%
Group 1: Box trucks, vans, buses with two axles, yard tractors, light-duty package delivery vehicles	2025	2028	2031	2033	2035 and beyond
Group 2: Work trucks, day cab tractors, buses with three axles	2027	2030	2033	2036	2039 and beyond
Group 3: Sleeper cab tractors and specialty vehicles	2030	2033	2036	2039	2042 and beyond

109 CARB (2023) Advanced Clean Fleets Regulation Summary. Retrieved from: https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-fleets-regulation-summary

The summary of sales and manufacturing regulations in California, U.S. and Canada are provided below in Table B.3.

Table B.3 Zero Emission HDV Regulations in California, U.S., and Canada

Scope	Jurisdiction	Targets for operations of HDVs	Regulations to manufacture and sell ZEV HDVs - Class 8
Regional/State	California	100% ZEV operations of all MHDV by 2045 where feasible[110] Interim targets for high priority fleets, drayage trucks and public fleets are described in Table 9 and Table 10 as per the *Advanced Clean Fleet Rule*	**Advanced Clean Truck Rule** By 2035, zero emission sales: 75% for Class 4-8 rigid trucks 40% for Class 7-8 tractor trucks **Advanced Clean Fleet Rule** Starting in 2036: sell only zero emission MHD vehicles
Regional/State	Colorado, Connecticut, Hawaii, Maine, Maryland, Massachusetts, Nevada, New Jersey, New York, North Carolina, Oregon, Pennsylvania, Rhode Island, Vermont, Virginia, and Washington Connecticut, Maine are working on adopting the rule.[111]		Same as California's Advanced Clean Truck Rule
Federal	Canada and U.S.		Global MOU By 2030: 30% zero emission MHDV new sales By 2040: 100% zero emission MHDV new sales[112]
Regional/ Provincial	British Columbia		The province of BC is in the process of creating a sales mandate for MHD in alignment with California's rules

110 Governor Newsom Announces California Will Phase Out Gasoline-Powered Cars & Drastically Reduce Demand for Fossil Fuel in California's Fight Against Climate Change, Office of Governor Gavin Newsom, 2020, https://www.gov.ca.gov/2020/09/23/governor-newsom-announces-california-will-phase-out-gasoline-powered-cars-drastically-reduce-demand-for-fossil-fuel-in-californias-fight-against-climate-change/

111 Electric Trucks Now (2023), States are embracing electric trucks. Retrieved from: https://www.electrictrucksnow.com/states

112 Global Memorandum of Understanding On Zero-Emission Medium- And Heavy-Duty Vehicles (2024). Retrieved from: https://globaldrivetozero.org/mou-nations/

Appendix C
Financial Incentives

Canada – Federal

Incentives for Medium- and Heavy-Duty Zero-Emission Vehicles (iMHZEV) Program
The *Incentives for Medium- and Heavy-Duty Zero-Emission Vehicles (iMHZEV) Program* was launched in July 2022 by Transport Canada and offers Canadian for profit and not-for-profit organizations, provinces, territories, and municipalities $547.5M worth in incentives towards the purchase or lease of eligible MHZEVs. The program is ongoing until 2026 or until the fund pool is exhausted.[113]

The maximum available incentive for each vehicle is $200,000 with a limit of 10 incentives per organization or a maximum of $1 million, whichever comes first, per calendar year. As of January 2023, the only eligible Class 8 vehicles are battery electric and hydrogen fuel cell tractors and trucks. Exclusions to the program consists of off-road vehicles, pre-owned vehicles, and vehicles purchased or leased outside of Canada. This federal incentive will be applicable to qualifying MHZEVs, supplementing any provincial or territorial incentive, and can cover up to 75% of the Manufacturer's Suggested Retail Price (MSRP) of the vehicle. [114]

For leased vehicles, incentives are described in Table C.1 below.

Table C.1: Maximum incentive for leased vehicles [115]

Vehicle class	Full incentive amount	48-month lease	36-month lease	24-month lease	12-month lease
8 (Coach, FCEV)	$200,000	$200,000	$150,000	$100,000	$50,000
8 (≥350 kWh)	$150,000	$150,000	$112,500	$75,000	$37,500
8 (<350 kWh)	$100,000	$100,000	$75,000	$50,000	$25,000

The list of eligible vehicles is being constantly updated by Transport Canada. The full list can be found on the Transport Canada website.

Zero Emission Vehicle Infrastructure Program
Finally, to encourage the adoption of more zero emission infrastructure, fleet operators can get up to 50% of funding for private commercial charging and refueling station installations to support their fleet's needs, through Natural Resources Canada's *Zero Emission Vehicle Infrastructure Program (ZEVIP)*.[116] The initiative will provide a total of $680 million in incentives to enhance the accessibility of localized charging and hydrogen refueling options for all Canadians. Three main streams for funding are available until 2027: owners/operators of ZEV infrastructure, delivery organizations, and Indigenous organizations. The project focus is on implementation of EV and hydrogen chargers in public places, on-street, in multi-unit residential buildings, at workplaces, and for vehicle fleets. The minimum charging and refueling requirements are well below what would be required for Class 8 long haul vehicles (e.g., 100 kW fast charger or 350 bar hydrogen dispensing). Note that according to the funding requirements, the group "delivery organizations" is for smaller and localised EV charging initiatives costing less than $100,000, and therefore is not relevant to Class 8 long-haul trucks.

Canada – Provincial

Provincial funding programs for HDZEVs are limited to Quebec, British Columbia, and Nova Scotia.

Quebec
In Québec, since December 2021, under the *Programme Écocamionnage* commercial freight vehicle operators (i.e., businesses, individuals, organizations or municipalities) who hold

113 Transport Canada (2023), Medium- and heavy-duty zero-emission vehicles. Retrieved from: https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles/medium-heavy-duty-zero-emission-vehicles

114 Transport Canada (2023) iMHZEV – Questions and answers. Retrieved from: https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles/medium-heavy-duty-zero-emission-vehicles/imhzev-questions-answers

115 Transport Canada (2023) iMHZEV – Questions and answers. Retrieved from: https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles/medium-heavy-duty-zero-emission-vehicles/imhzev-questions-answers

116 Natural Resources Canada (2024), Zero Emission Vehicle Infrastructure Program. Retrieved from: https://www.nrcan.gc.ca/energy-efficiency/transportation-alternative-fuels/zero-emission-vehicle-infrastructure-program/21876

registration in the Registre des propriétaires et des exploitants de véhicules lourds (RPEVL) with satisfactory safety rating can benefit from 50% off the incremental cost of a new electric or fuel cell truck up to CAD $75,000.[117] Additional financial aid is provided if the technology is installed in Quebec (5% bonus), if the technology is assembled or manufactured in Quebec (10% bonus), and if the technology meets the two previous criteria (15% bonus). Incentives are also provided to the purchase of used heavy vehicles and collaborative electric delivery projects. These projects must aim to increase freight transportation efficiency and reduce GHG emissions, through collaboration between different entities such as municipalities, non-profit legal entities and cooperatives headquartered or operating in Quebec for at least two years.[118]

Fleet operators can also receive financial support for consulting, fleet electrification, and roadmap design from consulting companies. This incentive is provided through the Quebec Ecoleader program with supports of up to $60,000 or 75% of eligible costs. [119]

British Columbia
The Province of British Columbia has supported the adoption of MHD ZEV since 2018, through the *CleanBC Go Electric Program*, which provides incentives for the deployment of commercial zero emission vehicles and infrastructure under the *Go Electric Commercial Vehicle Pilot Program (CVP)* and post-purchase rebates under the Go Electric Rebates (formerly Specialty Use Vehicle Incentive Program - SUVI) . Under the latter incentive, companies can access up to 33% of the cost of eligible medium or heavy-duty vehicle with an increased maximum cap of $150,000, as of July 2023. [121]

In addition to those incentives, in August 2023, the Ministry of Energy, Mines and Low Carbon Innovation announced two major MHD sector investments. The first is a contribution of $19.5 million to build 130 new medium- and heavy-duty vehicle charging stations. The second is an incentive of $30 million to subsidize MHD ZEV technology development in BC under the Go Electric Commercial Vehicle Innovation Challenge.[122]

Nova Scotia
In April 2024, Nova Scotia introduced the province's first rebate program for medium- and heavy-duty zero-emission vehicles. Tory Rushton, Minister of Natural Resources and Renewables, emphasized the importance of transitioning to zero-emission vehicles to reduce greenhouse gas emissions and achieve the province's net-zero goal by 2050. Eligible vehicles include those used for commercial or industrial purposes weighing over 3,856 kilograms (8,500 pounds), along with electric resurfacing machines like Zambonis. Administered by Clean Foundation through the Electrify Nova Scotia Rebate Program, this pilot initiative offers rebates of up to $50,000 per vehicle to businesses, non-profits, municipalities, and Mi'kmaw communities.[123]

117 Transports et Mobilité durable Québec (2023), Programme Écocamionnage. Retrieved from: https://www.transports.gouv.qc.ca/fr/aide-finan/entreprises-camionnage/aide-ecocamionnage/Pages/aide-ecocamionnage.aspx

118 Transports et Mobilité durable Québec (2023), Programme Écocamionnage. Retrieved from: https://www.transports.gouv.qc.ca/fr/aide-finan/entreprises-camionnage/aide-ecocamionnage/Pages/aide-ecocamionnage.aspx

119 7GEN (2022), How government incentives support your transition to fleet electrification. Retrieved from: https://7gen.com/how-government-incentives-support-your-transition-to-fleet-electrification/#:~:text=Fleet%20operators%20can%20also%20benefit,or%2075%25%20of%20eligible%20costs.

120 Government of British Columbia (2023). B.C. Medium- and Heavy-Duty Zero-Emission Vehicles: 2023 Consultation Paper. Retrieved from: https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/bc_mhd_zev_2023_consultation_paper_20230516.pdf

121 Plug In BC Collaborative (2023), PlugInBC, Retrieved from: https://pluginbc.ca/goelectricrebates/

122 BC Ministry of Energy, Mines and Low Carbon Innovation (2023), B.C. drives industry shift to cleaner heavy-duty transportation, Retrieved from: https://news.gov.bc.ca/releases/2023EMLI0021-000600

123 Government of Nova Scotia (2024). New Rebates for Larger Zero-Emission Vehicles. Retrieved from: https://news.novascotia.ca/en/2024/04/02/new-rebates-larger-zero-emission-vehicles

Appendix D

Summary of electricity distribution system upgrades for charging site

It is assumed that the cost of fast charging infrastructure will be incurred by charging station operators and potentially electrical utilities across long-haul corridors. The table below presents the estimated upgrade costs in the U.S. for a large-scale charging hub, not including the costs of higher power (1000-3750 kW) MCS chargers that are still not currently commercially available. [124]

Component category	Upgrade	Typical cause for upgrade	Typical cost	Typical timeline (months)
Customer on-site	150 kW DCFC		Procurement, US$75,000-100,000 per plug; installation, US$19,000-48,000 per plug	3-10
	350 kW DCFC		Procurement, US$128,000-150,000 per plug; installation, US$26,000-66,000 per plug	
Utility on-site	Install distribution transformer	200+kW load	Procurement US$12,000-175,000	3-8
Distribution feeder	Install/upgrade feeder circuit	5+ MW load	US$2-12 million	3-12
Distribution substation	Add feeder breaker	5+ MW load	~US$400,000	6-12
	Substation upgrade	3-10+ MW load	US$3-5 million	12-18
	New substation installation	3-10+ MW load	US$4-35 million	24-48

124 Brennan Borlaug, et al. (2021). Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems, Nature Energy, Vol. 6. Retrieved from: https://doi.org/10.1038/s41560-021-00855-0

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