UNIVERSITY OF CALGARY

# The Transition to Net-Zero of Heavy-Duty Road Freight in Alberta: A Scenario Model

by

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# Abstract

The global climate crisis has prompted Canada's commitment to achieving net-zero greenhouse-gas (GHG) emissions by 2050. The transportation sector, responsible for ~25% of Canada's GHG emissions, faces challenges in decarbonizing heavy-duty vehicles (HDVs), which make up ~20% of transportation emissions. Alberta's heavy-duty trucking industry, a significant emissions contributor, encounters challenging conditions with strict range and vehicle weight requirements, complicating efforts to decarbonize.

This thesis models the transition of Alberta's heavy-duty trucking sector to net-zero GHG emissions, evaluating the feasibility of meeting Canada's federal targets of 35% zero-emission vehicle (ZEV) sales by 2030 and nearly 100% by 2040. A comprehensive stock and flow model for hydrogen fuel-cell electric vehicles (FCEVs) and battery electric vehicles is developed, integrating vehicle projections, kilometers traveled, energy use, and GHG emissions under different decarbonization scenarios.

The study also explores the development of a hydrogen-based value chain for Alberta's long-haul trucking industry, addressing the economic, logistical, and technical challenges of building infrastructure to support FCEVs. The economic analysis compares the total cost of ownership (TCO) for FCEVs and internal combustion engine vehicles (ICEVs) and examines the role of government policies, particularly the carbon tax, in supporting the transition.

Key findings indicate that meeting the 2030 sales target is unlikely due to infrastructure and deployment challenges, while the 2040 target, though challenging, remains feasible. The extended timeline allows for the development of zero-emission vehicle technologies and hydrogen infrastructure, providing substantial GHG emission reduction benefits of at least 87% across all scenarios. FCEVs initially have a higher TCO than ICEVs, but as production scales and technology improves, the TCO is projected to fall below ICEVs by 2045. Incremental costs are projected to peak at CAD 500 million annually by 2035, achieving cost parity by 2040, and resulting in total costs of CAD 4 billion, with potential savings of up to CAD 2.5 billion annually by 2050. The projected carbon tax revenue covers the incremental costs, and even if doubled, would require only 75% of the revenue, demonstrating the strong economic feasibility of this beneficial and essential transition.

# Preface

This thesis comprises a collection of works, some of which have been previously published or are under review, and others adapted from existing resources with appropriate permissions where necessary.

**Chapter 3** of this thesis has been submitted for publication as an article titled *Net-Zero Transition Model of Alberta's Heavy-Duty Trucking Sector* to Transportation Research Part D: Transport and Environment and is currently under review.

**Figures** within this thesis have been adapted or directly taken from various sources:

- **Figure 2.2.** has been adapted from the forthcoming NZEST report by Dr. David Layzell (Layzell et al., In press).
- **Figure 2.3.** is adapted from the US Alternative Fuels Data Center (Alternative Fuels Data Center, 2012).
- **Figure 2.4.** is adapted from Figure 8.1 of the Transition Accelerator report (Layzell et al., 2023).
- **Figure 2.6.** is sourced from R. Dervisoglu's work, based on public domain images available via Wikimedia Commons (Dervisoglu, 2012).
- **Figure 4.4.** is a schematic overview of the HDRSAM Model, sourced from (Argonne National Laboratory, 2017).
- **Figure 4.5.** is sourced directly from Figure 6 of (Sharpe and Basma, 2022).
- **Figure 4.7.** is sourced from Figure 5.11 of (Khan et al., 2022).
- **Figure 5.1.** is sourced and adapted with additional information from IDTechEx Research (Siddiqi, 2023).

Each chapter and figure have been carefully cited to acknowledge the original sources and authors.

## Acknowledgements

I would like to acknowledge the financial support that made this research possible. The AZETEC Project, through CESAR at the University of Calgary, provided key funding, alongside the support from NSERC (Natural Sciences and Engineering Research Council of Canada) through both the Integrated Infrastructure for Sustainable Cities (IISC) project and Dr. de Barros. I am also grateful to The Transition Accelerator for their collaboration and support, particularly through Dr. Layzell. Additionally, I extend my thanks to CREATE – IISC at the University of Calgary for offering valuable training and insight into the impact of disruptive forces on urban infrastructure systems. Finally, I am deeply appreciative of the encouragement and support from my family, friends, and my supervisors Dr. David Layzell and Dr. Alex de Barros who mentored me throughout this journey.

## Dedication

To my Mom, Dad, and Sister, my incredible family who have given me the strength, love, and support to face every challenge, especially during my recent tough times. Your love for science and curiosity about the world have always inspired me, and your belief in me has carried me further than you know. I love you three so much, and it is because of you that I strive every day to grow and learn, to one day be just as remarkable as you all are.

To my supervisors, Dr. Layzell and Dr. de Barros, whose guidance and mentorship have been invaluable to my growth as a researcher and scientist, I am deeply grateful. Thank you, from the bottom of my heart.

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## List of Abbreviations

ANL – Argonne National Laboratory

ATR – Auto Thermal Reforming

BAU – Business-As-Usual

BEV – Battery Electric Vehicle

CAD – Canadian Dollars (2020)

CCS – Carbon Capture and Storage

$CO_2e$ – Carbon Dioxide Equivalent

EV – Electric Vehicle

FCEV – Fuel Cell Electric Vehicle

GHG – Greenhouse Gas

GVW – Gross Vehicle Weight

HDRSAM - Heavy-Duty Refueling Station Analysis Model

HD – Heavy-Duty

HDV – Heavy-Duty Vehicle

HHV – Higher Heating Value

ICEV – Internal Combustion Engine Vehicle

IMAL – Insurance, Maintenance, Administration, and Labour

LH – Long-Haul

MD – Medium-Duty

MS – Market Share

NZ – Net-Zero

SH – Short Haul

SMR – Steam Methane Reforming

TCO – Total Cost of Ownership

VKT – Vehicle Kilometres Travelled

ZEV – Zero Emission Vehicle

000s – Thousands

$ – 2020 Canadian Dollars (2020 CAD)

# 1. Introduction

The current global climate crisis, driven by the accumulation of greenhouse gases (GHGs) such as carbon dioxide ($CO_2$) and methane ($CH_4$) in the atmosphere, presents a dire challenge to the environment and human society. These gases trap solar radiation, leading to rising global temperatures, which in turn cause several known detrimental environmental effects like the melting of polar ice caps, rising sea levels, crop failures, and an increase in the frequency and severity of extreme weather events (Walsh et al., 2020). As human caused GHG emissions increase, there is a concern these emissions will trigger 'runaway' GHG emissions from melting permafrost, burning forests, or ocean acidification, further accelerating climate change and potentially rendering ineffective, future mitigation efforts (Anderegg et al., 2020; Natali et al., 2021).

In response to these escalating climate threats, countries around the world have committed to achieving net-zero (NZ) GHG emissions on a national level (Lang, 2023). This ambitious goal is part of a broader global effort to mitigate the most severe impacts of climate change. However, the transition to net-zero is not uniform for all countries, or even across all sectors, as some face significant barriers to decarbonization due to their reliance on fossil fuels and other carbon-intensive practices. For Canada, addressing these challenges is particularly crucial, given the country's significant contributions to global emissions, reliance on the fossil fuel industry, and its vulnerability to the impacts of climate change (Ford et al., 2018; Talaei et al., 2020). The path to net-zero will require coordinated efforts across all sectors of the economy, with particular focus on those that are hardest to decarbonize.

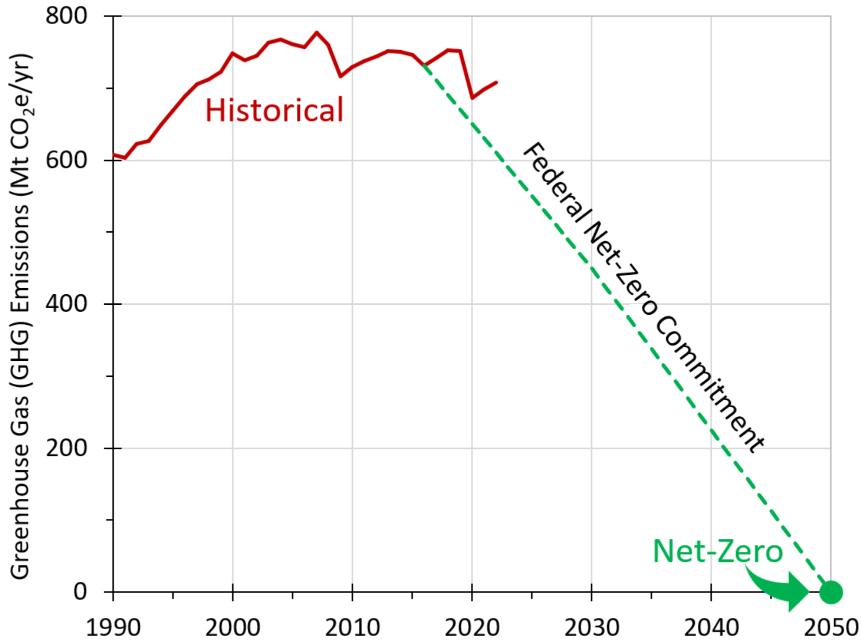



**Fig. 1.1.** Canada's Historical GHG Emissions in 2022.
*Data from the 2023 NIR report (Environment and Climate Change Canada, 2023)*

To address the growing threat of climate change, Canada, along with other countries, has committed to achieving net-zero GHG emissions by 2050 (Government of Canada, 2021; Lang, 2023). Despite more than 25 years of previous climate change policy however, Canada has only managed to stabilize its greenhouse-gas emissions (**Fig. 1.1**) rather than achieve any meaningful reduction. To meet its net-zero target within the next 25 years, Canada must significantly reduce emissions to near zero and may need to employ negative emission technologies for sectors that are lagging in GHG reductions or just outright challenging to decarbonize. This presents a significant challenge, particularly since in 2019 (pre-COVID), Canada's GHG emissions stood at 738 Mt $CO_2e$/yr, with ~81% of these emissions linked to energy production and consumption (**Fig. 1.2**).

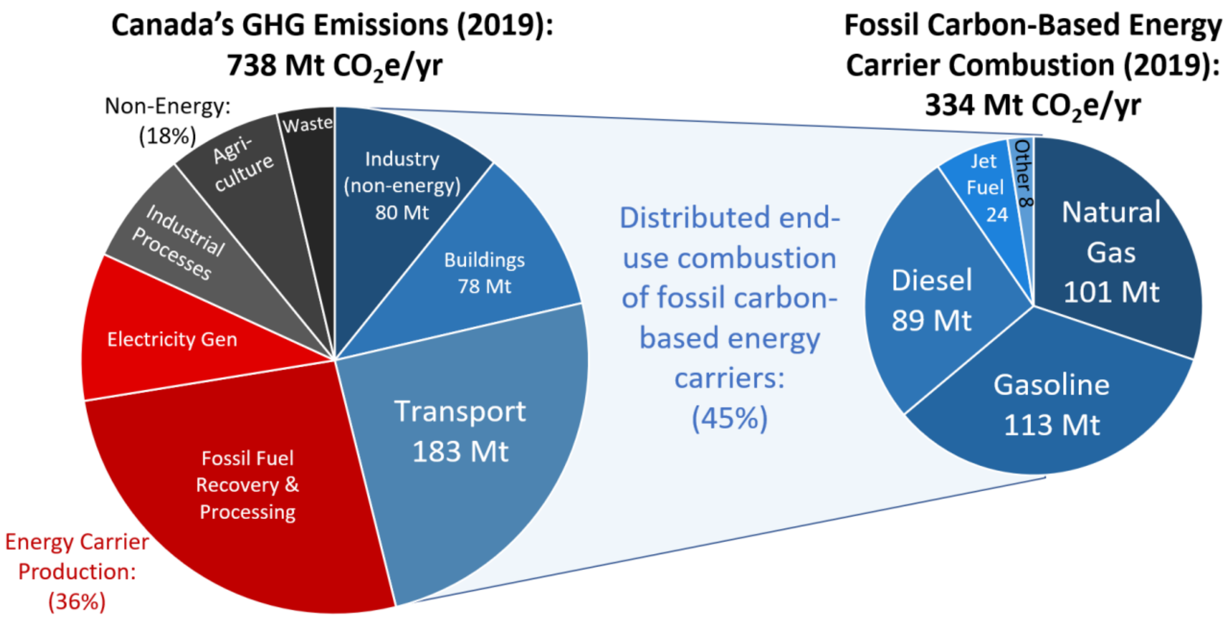



**Fig. 1.2.** Breakdown of Canada's GHG Emissions in 2019.
*Data taken from: (Environment and Climate Change Canada, 2023; Natural Resources Canada, 2023a)*

As a major energy-exporting nation, Canada is responsible for significant emissions from energy carrier production due to its large-scale extraction and processing of oil and natural gas, about 36% of its national emissions (**Fig 1.2**). Additionally, 45% of Canada's total emissions come from the end-use combustion of these energy carriers, such as gasoline, diesel, jet fuel, and natural gas (**Fig 1.2**). To meet net-zero targets, Canada must transition from carbon-intensive energy carriers to zero-emission alternatives and adopt greener technologies across all sectors.

Given Canada's commitment to net-zero emissions, the transportation sector—responsible for approximately ~25% of the country's GHG emissions (**Fig 1.2**)—emerges as a critical focus. Dominated by internal combustion engine vehicles (ICEVs), the sector presents a significant challenge for decarbonization. Since vehicles are considered long-term investments, many ICEVs sold today are likely to remain in regular use for 10, 15, or even more than 20 years, continuing to emit greenhouse gases despite the urgent need for a transition to net-zero. Compounding the issue, Canada's economic reliance on the oil and gas industry, particularly in provinces like Alberta, creates a direct conflict with the nation's goal to transition away from carbon-intensive industries. As well, Canada's unique geographical and climate conditions present significant hurdles that are not as prevalent in other major countries. These include extreme temperatures that can drop below -40°C and vast distances between major cities, which can strain the capabilities of new vehicle technologies (Davidson et al., 2024).

Recognizing these challenges, the Government of Canada remains committed to supporting the transportation sector's transition to net-zero. A key target has been set for personal vehicles, mandating that 100% of light-duty vehicle sales (including cars, SUVs, and light-duty trucks) be zero-emission vehicles (ZEVs) by 2035, effectively banning the sale of new personal ICEVs that same year (Environment and Climate Change Canada, 2022a). This policy provides both incentives for automakers to transition to ZEV production and a reasonable timeline for the shift to occur. While similar mandates have been adopted by other countries (Lang, 2023) leading many automakers to move away from ICEVs, the transition becomes far more complex when addressing the broader transportation sector beyond personal vehicles.

The main transition challenge is not with personal vehicles, but in decarbonizing heavy-duty vehicles (HDVs). Class 8 HDVs, with gross vehicle weights (GVW) of 15 to 63.5 tonnes, account for nearly 20% of Canada's transportation GHG emissions, or 35 Mt $CO_2e$/year (Environment and Climate Change Canada, 2023). The HDV sector's heavy loads, need for rapid refuelling, and long-range requirements, with an average of 86,900 km/vehicle/year for Canada's 489,000 Class 8 trucks in 2019, make it particularly difficult to decarbonize. In response, the Canadian government has set ambitious but distinct targets for HDVs, aiming for 35% of new HDV sales to be ZEVs by 2030 and nearly 100% by 2040 (Environment and Climate Change Canada, 2022a). Continuing with traditional diesel-powered ICE-HDVs has significant environmental impacts, contributing to both local air pollution and global climate change (Zalzal and Hatzopoulou, 2022). Decarbonizing heavy-duty freight transport requires examining the entire value chain, from the energy source (the 'well') to the vehicle's operation (the 'wheel'). This includes the production and transportation of energy carriers, vehicle manufacturing, infrastructure development, and fleet logistics. Optimizing this entire chain is essential for reducing environmental impacts and improving the efficiency and reliability of low or net-zero GHG technologies (Khan et al., 2022).

To achieve Canadian net-zero targets, HDVs need zero-emission energy carriers. When coupled with an electric drivetrain, significant efficiency improvements can be achieved in converting energy to kilometres travelled, compared to internal combustion engines (Anselma and Belingardi, 2022; Cullen et al., 2021). Hydrogen ($H_2$) and its derivatives, such as ammonia ($NH_3$), are emerging as promising zero-emission energy carriers, particularly in sectors like HDVs where electrification is less feasible (Cullen et al., 2021; Li et al., 2022a; Pardhi et al., 2022). When hydrogen is used in fuel cells to generate electricity in hydrogen fuel cell electric vehicles (FCEVs), it produces only water vapor as a byproduct, offering an efficient and zero-emission solution for decarbonizing heavy-duty transport.

Hydrogen combustion in ICEs also produces water vapor but generates small amounts of nitrogen oxides (NOx), which are GHGs. As a result, hydrogen combustion is not classified as a true zero-emission technology and lacks the efficiency gains and regenerative braking capabilities of FCEVs. However, the minimal NOx emissions from hydrogen combustion are significantly lower compared to diesel emissions, which complicates its role as a transitional technology. While hydrogen has shown a lot of promise as a zero-emission energy carrier, a major challenge with hydrogen lies in its production methods. Currently, hydrogen is primarily produced by splitting natural gas, which results in significant upstream GHG emissions (International Energy Agency, 2020). However, lower-emission methods, such as natural gas splitting with carbon capture and the clean production of hydrogen through water electrolysis, are becoming more common and will be important in ensuring hydrogen's low-GHG usage.

For long-haul (LH) heavy-duty freight, hydrogen fuel cell electric vehicles are increasingly recognized as the most promising zero-emission option due to their fast refuelling capabilities and lower weight compared to range-equivalent battery electric vehicles (BEVs) (Burke, 2020; Burke et al., 2023; Cunanan et al., 2021). Long-haul internal combustion engine (ICE) vehicles typically travel over 200,000 km per year during their first four to five years, after which they are often sold into the short-haul (SH) market, where annual vehicle kilometres travelled (VKT) are much lower (Alberta Motor Transport Association, personal communication). If this practice continues in the shift to ZEVs, many FCEVs are likely to enter the SH market as well. A major challenge for FCEVs is not only producing vehicles that meet the freight sector's requirements but also developing an entirely new value chain to support the production, transport, and delivery of fuel cell-grade hydrogen to sustain the entire HDV sector and beyond, seen in the **Fig. 1.3** diagram below.

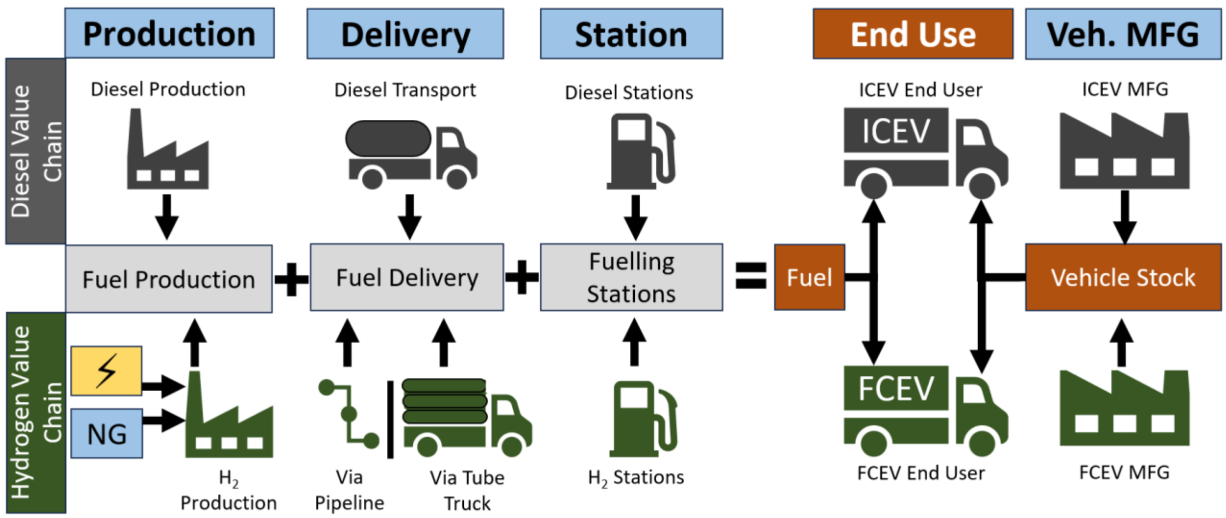
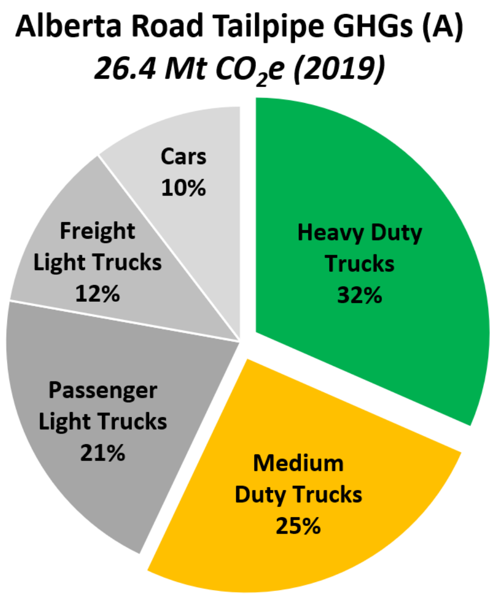



**Fig. 1.3.** Hydrogen and Diesel Value Chain Diagram

Aside from hydrogen, electricity stored in batteries is another promising zero-emission energy carrier, provided it is generated with minimal or no GHG emissions. However, electricity presents challenges in sectors like heavy-duty transportation due to limitations in energy density, storage, and the required infrastructure (Cunanan et al., 2021).

Battery electric vehicles in the HDV sector are well-suited for short-haul, return-to-base operations (ideally covering less than 200 km/day), enabling overnight charging and sufficient on-board storage without compromising hauling capacity (Forrest et al., 2020). From a total cost of ownership perspective, BEVs perform well in smaller-scale operational settings (Anselma and Belingardi, 2022), but their advantage diminishes with larger fleets, multiple driver shifts (Hunter et al., 2021), or trips exceeding 500 kilometres (Burke et al., 2023).



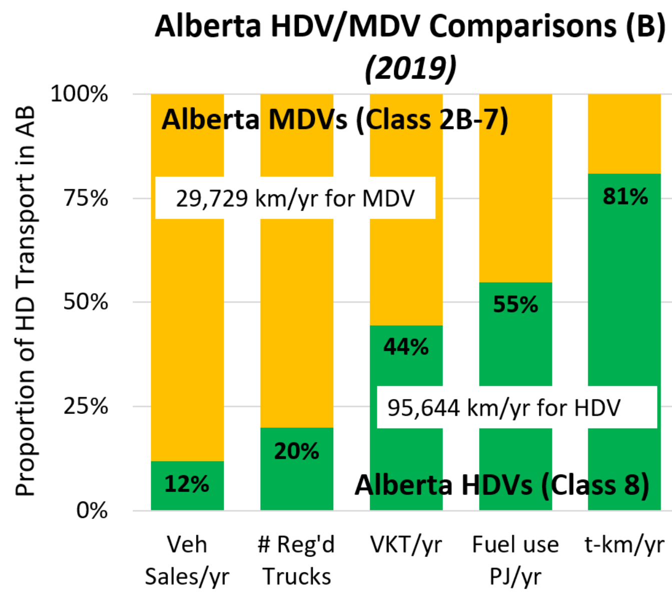




**Fig. 1.4.** Alberta Road Tailpipe Greenhouse-Gasses in 2019 (**A**), and Comparison of Alberta Heavy-Duty and Medium-Duty Vehicles in 2019 (**B**).
*Alberta road tailpipe greenhouse gas emission sources are compared (**A**), along with the comparison of heavy-duty and medium-duty vehicles in the categories of vehicle sales per year, number of registered trucks, vehicle kilometers travelled (VKT) per year, fuel use in petajoules per year, and tonne-kilometers of freight towed per year (**B**).*

The challenge of transitioning Class 8 HDVs to net-zero is particularly evident in Alberta, where the heavy-duty trucking industry is much more concentrated than in other provinces. Although Alberta accounts for only 12% of Canada's population and 14% of its light-duty gasoline trucks, it is home to 23% of the country's heavy-duty trucks (Natural Resources Canada, 2023a). In 2019, Alberta's HD trucks emitted over three times more $CO_2e$ than cars, and 24% more GHGs than medium-duty (MD) trucks, despite there being four times more registered MD trucks (**Fig. 1.4**). Alberta's HD trucking sector has several potential pathways to net-zero, including BEVs and FCEVs as true zero-emission options, along with transitional technologies like biofuels, HD2F, and PHEVs. Assessing the potential for this transition will provide valuable insights into the challenges, costs, benefits, and feasibility of achieving net-zero GHG emissions in this sector, not only for Alberta but for the rest of Canada.

Given this context, Alberta and its heavy-duty trucking sector have been chosen as the focus of this thesis, with an emphasis on transitioning and decarbonizing this sector to meet the Canadian government's net-zero targets for HDVs.

## 1.1 Research Objective

The primary objective of this thesis is to model the transition of Alberta's heavy-duty trucking sector to net-zero GHG emissions, evaluating the feasibility of meeting Canada's HDV sales targets and analyzing the comprehensive costs and logistical implications of building a new hydrogen value chain supporting FCEVs. This research aims to guide policy and investment decisions for the government, hydrogen industry, and trucking sector, highlighting the challenges and potential economic and environmental benefits of adopting fuel cell and battery electric vehicles in Alberta. Ultimately, the thesis provides a strategic roadmap for achieving a sustainable and economically viable net-zero transition for Alberta's heavy-duty trucking sector.

## 1.2 Proposed Methodology and Contributions

This thesis develops an integrated modelling and economic framework to analyze the transition of Alberta's heavy-duty vehicle sector to net-zero emissions by 2050, with a focus on the hydrogen fuel cell electric vehicle value chain, and the feasibility of meeting the Canadian HD-ZEV targets of 35% ZEV sales by 2030 and 100% by 2040. The methodology is built on a combination of transportation stock and flow modeling, GHG life cycle analysis, and economic evaluation, which together provide a comprehensive assessment of the feasibility, costs, and benefits of transitioning from internal combustion engine heavy-duty vehicles to zero-emission alternatives.

Several key contributions are made to the modeling and assessment of HDV transitions:

- **Developing a comprehensive stock and flow model** that integrates vehicle sales projections, vehicle registrations, kilometers traveled, energy use, and greenhouse gas (GHG) emissions under different decarbonization scenarios for Alberta's HDV sector.
- **Incorporating a comprehensive life-cycle analysis** to evaluate the GHG emissions and environmental impact of the full HDV value chain, from energy production to fuel consumption and end-of-life processes.
- **Analyzing the logistics of transitioning to a hydrogen economy**, including the development of new infrastructure for hydrogen production, transportation, and fuelling stations, which supports the deployment of FCEVs.

This research explores the development of a hydrogen-based value chain for Alberta's heavy-duty trucking sector, providing insights into the economic, logistical, and technical challenges of building the infrastructure needed to support FCEVs:

- **Modeling hydrogen production and transport infrastructure**, including the costs and logistics of producing fuel cell-grade hydrogen and delivering it to fuelling stations.
- **Estimating the incremental costs** associated with the transition, including fuel production, transport, fuelling infrastructure, and vehicle costs, with a focus on the total cost of ownership for hydrogen-powered HDVs compared to diesel-powered HDVs.
- **Evaluating different hydrogen supply options**, such as centralized versus decentralized production, and analyzing their feasibility in terms of delivery, cost, and scalability.
- **Analyzing the scalability of hydrogen refuelling stations** and the potential economic benefits of expanding hydrogen infrastructure to meet growing demand as more FCEVs are deployed and the hydrogen economy grows.
- **Identifying potential funding sources** and examining the role of carbon pricing, government subsidies, and possibly public investment in supporting the transition.
- **Assessing the sensitivity of the economic model** to key variables such as future fuel prices, government policies, and technology advancements to highlight the potential risks and uncertainties in the transition.

Overall, this thesis contributes a detailed and multi-dimensional analysis of the transition of Alberta's HDV sector to a net-zero emissions future, focusing on the economic, logistical, and environmental implications of adopting hydrogen as a zero-emission energy carrier. The research provides policymakers, industry stakeholders, and investors with the necessary information to make informed decisions about the viability of FCEVs and the broader hydrogen economy.

**Statement of Contribution:**

**Chapter 3**, *Net-Zero Transition Model of Alberta's Heavy-Duty Trucking Sector*, was co-authored with my supervisors, Dr. David B. Layzell and Dr. Alexandre G. de Barros. This chapter has been submitted for publication to *Transportation Research Part D: Transport and Environment* and is currently under review. I was the primary researcher and author of this work. My contributions included assisting in the conceptualization, formal analysis, investigation, and methodology. I was responsible for the validation and visualization of the research findings. Additionally, I wrote the original draft and contributed to the review and editing of the manuscript. Dr. David Layzell contributed significantly to the development of the research question, conceptualization, investigation, and methodology of the research. He also played a key role in project administration, supervision, validation of the research findings, and provided critical review and editing of the manuscript. Dr. de Barros contributed to the conceptualization of the research. He provided supervision and assisted in the review and editing of the manuscript, ensuring its scientific accuracy and clarity.

## 1.3 Organization of the Thesis

This thesis is structured into five chapters and organized as follows:

**Chapter 2** reviews the current state of energy use and GHG emissions in Canada's HDV sector. It explores pathways to low and net-zero emissions, with particular attention to ICEs, electric drivetrains, and hydrogen, providing a foundation for the logistical and economic modelling in later chapters.

**Chapter 3** models the transition of Alberta's HDV sector to net-zero emissions, projecting HDV sales, registrations, kilometres travelled, energy use, and GHG emissions across different scenarios. It also evaluates the feasibility of meeting government targets, models life cycle GHG emissions, and examines the challenges of building a new hydrogen value chain to support FCEVs.

**Chapter 4** assesses the economic implications of transitioning Alberta's HDV sector to a hydrogen-based value chain supporting FCEVs. It estimates incremental costs, compares them with the sector's economic contributions, and covers fuel production, transport, fuelling stations, and total cost of ownership for FCEVs. It identifies potential funding sources and evaluates economic sensitivities, offering an initial cost estimate and highlighting challenges.

**Chapter 5** concludes the thesis by summarizing key findings, discussing policy and industry implications, and providing recommendations for future research. It also addresses the study's limitations and suggests areas for further investigation to support Alberta's net-zero transition in heavy-duty transportation.

# 2. Towards the Decarbonization of Freight Transportation

## 2.1 Energy Use and GHG Emissions from Transportation in Canada

Transportation is a major contributor to greenhouse gas emissions in Canada, accounting for approximately 189 Mt $CO_2$ per year, which represents 26% of the nation's total GHG emissions (Natural Resources Canada, 2023a). The sector includes a variety of vehicle types, each contributing differently to the overall emissions profile. To better understand the impact of different transportation modes, **Fig. 2.1** provides a breakdown of the GHG emissions from various vehicle categories within Canada for the year 2019 (pre-Covid pandemic). This figure serves as a starting point for analyzing the importance of each vehicle type, while highlighting the significant role that road freight plays in the country's transportation-related emissions.

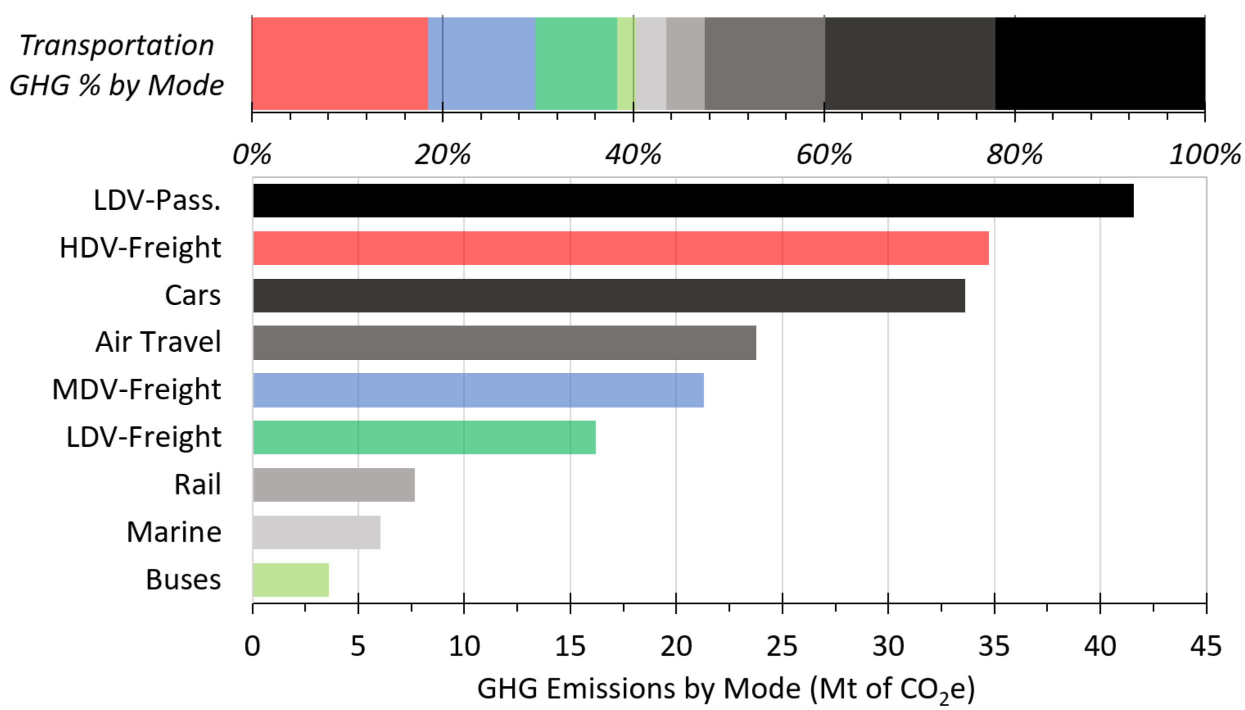



**Fig. 2.1.** GHG Emissions from Transportation in Canada in 2019.
*Data taken from the NRCan comprehensive energy use database (CEUD) (Natural Resources Canada, 2023a).*

While cars are often assumed to be the largest source of transportation emissions in Canada, **Fig. 2.1** shows that both light-duty passenger vehicles (LDV-Pass.), and more interestingly heavy-duty freight vehicles (HDVs) produced more emissions than personal cars in 2019. As described within the CEUD, LDV-Pass vehicles refer to light passenger trucks like the Ford F-150 and SUVs, which are not included within the "car" group and have different emissions standards applied to them (Government of Canada, 2022). In working towards the decarbonization of freight transportation, this puts heavy-duty freight emissions, and to a smaller extent medium-duty freight emissions, as the primary targets for this transition. Although heavy-duty freight and cars may have similar emissions profiles, these vehicle types have much different fuel requirements needed to meet their energy demands described in **Fig. 2.2** below.

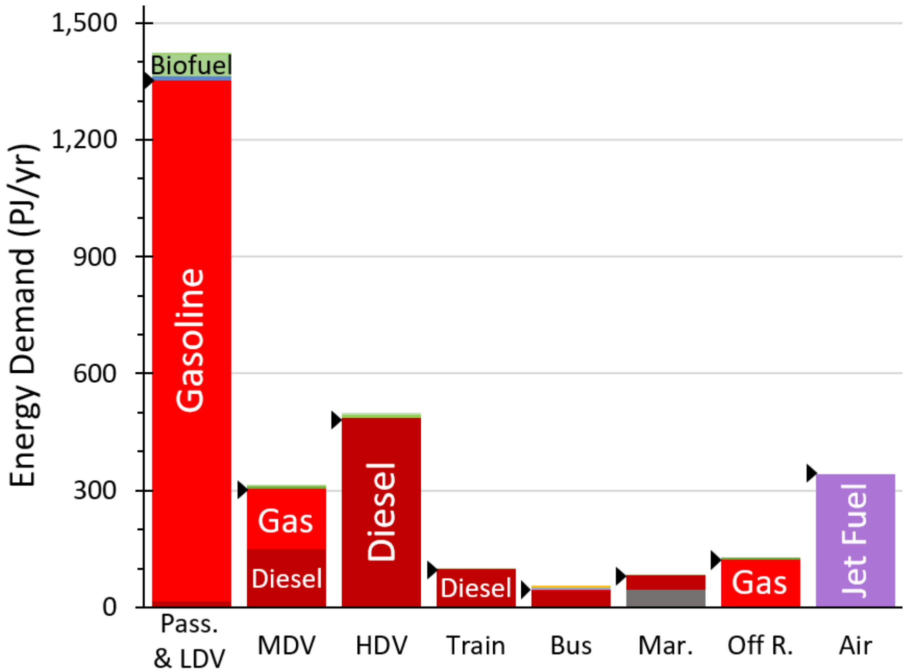



**Fig. 2.2.** Energy Use from Transportation in Canada in 2019.
*Pass. & LDV refers to cars, passenger light-duty, and freight light-duty vehicles. MDV refers to medium-duty vehicles, HDV refers to heavy-duty vehicles, Mar. refers to marine vehicles, and Off R. refers to off road vehicles. Data sourced from (Natural Resources Canada, 2023a), figure adapted from (Layzell et al., In press).*

**Fig. 2.2** provides a look at the distribution of different fuels used within Canada in 2019, with gasoline and diesel as the primary consumers of energy demand within the transportation industry. Marine transport and air transport are an outlier for fuel use, with marine transport primarily using heavy fuel oil for its energy demand, as well as air transport using exclusively jet fuel. The large energy demand for gasoline is seen within lighter-duty vehicles such as passenger light-duty vehicles, freight light-duty vehicles, off-road vehicles and about half of medium-duty vehicle usage. Diesel on the other hand, is primarily used within the heavier transportation fleets such as heavy-duty vehicles, longer haul medium-duty vehicles, trains, buses, and a bit less than half of marine transport. This fuel type difference is due to the higher energy density, better fuel efficiency under load, and superior torque that comes from diesel use in internal combustion engines, which is essential for heavy-duty applications (International Council on Clean Transportation, 2014). The reason for medium-duty vehicles' near equal usage of gasoline and diesel, comes from the much wider distribution of vehicles within this group covering both light- and heavier-duty applications, seen in **Fig 2.3**.

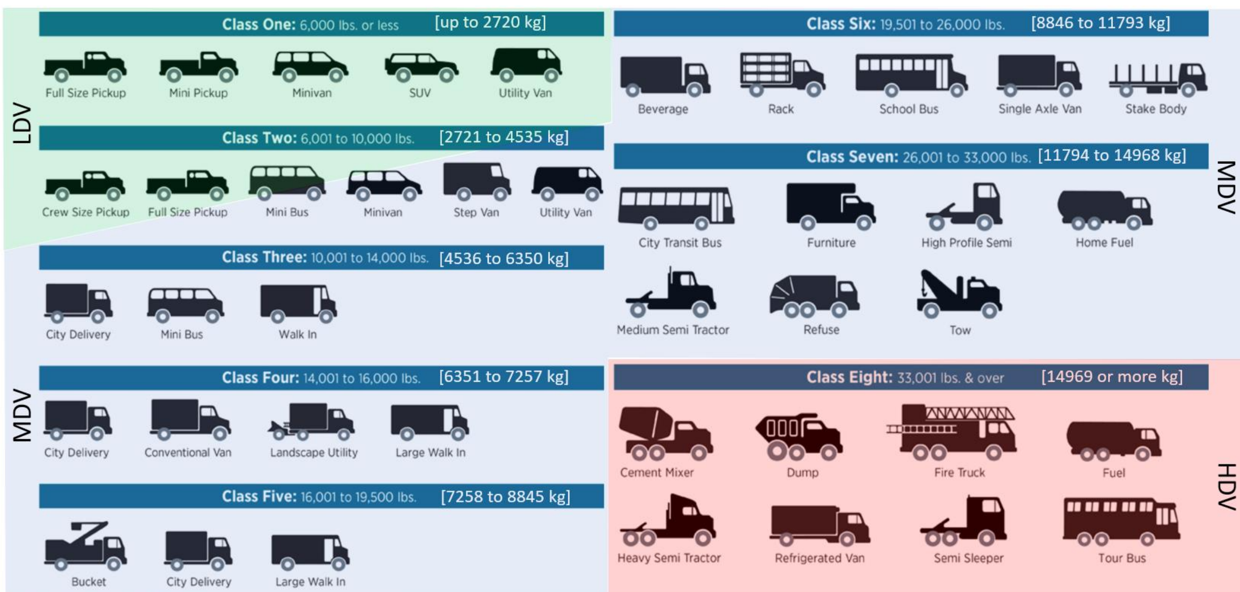



**Fig. 2.3.** Types of Freight Carrying Vehicles by Weight Class.
*This figure shows how the weight classes are associated with Canadian terminology for light-duty (LDV, green shading), medium-duty (MDV, blue shading), and heavy-duty vehicles (HDV, red shading). MDVs include gross vehicle weights of 3.9 to 15 tonnes. Image adapted from US Alternative Fuels Data Centre (Alternative Fuels Data Center, 2012).*

The majority of on road freight vehicles are found within the first two classes of vehicles, these of which being the primary users of gasoline (**Fig. 2.2**). **Fig. 2.3** adapted from the 2012 Alternative Fuels Data Center showcases the diversity within medium-duty vehicles, as Class 3 to Class 7 vehicles may be classified as medium-duty, with intermediates like the Class 4 Ford F-450 available in both gasoline and diesel models (Ford Motor Company, 2024).

This provides a challenge in the decarbonization of freight transportation, as with multiple vehicle classes and fuel types, it becomes difficult to know what area is most valuable for initial decarbonization efforts. This challenge is addressed in **Fig. 2.4** by comparing the three categories of vehicles based on total registrations, vehicle kilometres travelled (VKT), and fuel/energy consumption, to determine which area provides the greatest emission reduction potential.

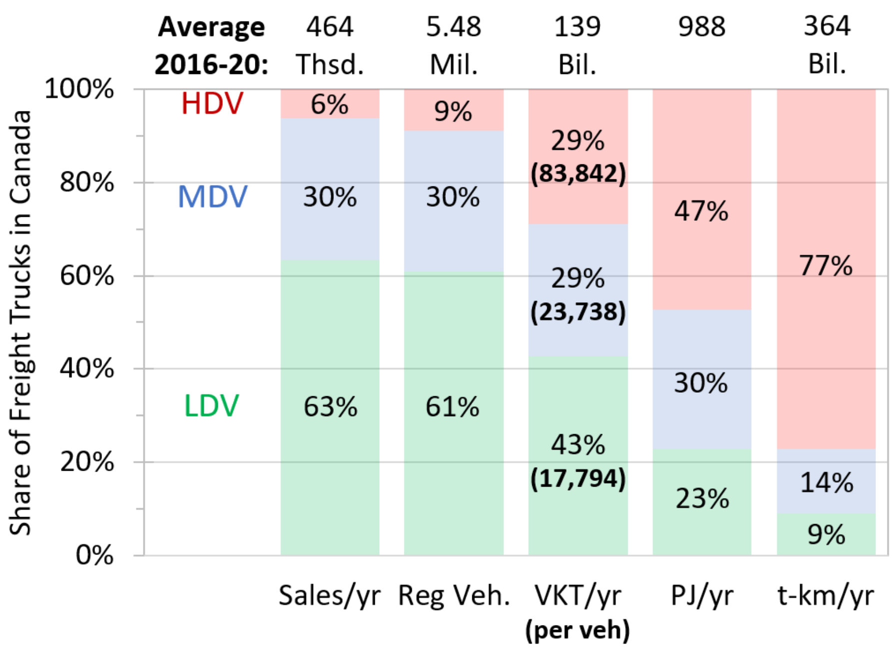



**Fig. 2.4.** Comparison of Light-Duty (LDV), Medium-Duty (MDV), and HDV Freight-Carrying Vehicles for Canada Averaged Across 2016-2020.
*Comparison done in terms of new vehicle sales/yr, registered vehicles on the road, total vehicle kilometers travelled (VKT) per year, $PJ_{HHV}$ fuel energy used per yr, and tonne-kilometer moved per year. All values are for all Canada averaged for the years 2016 to 2020 (Natural Resources Canada, 2023a). Total average annual values are provided at the top of each bar chart, and the values in parentheses are the average VKT/vehicle/yr for the registered vehicles associated with each vehicle class. Adapted from Figure 8.1 from the Transition Accelerator report (Layzell et al., 2023).*

In the context of Canada's freight transportation sector, heavy-duty vehicles emerge as a critical focus for addressing climate change from **Fig. 2.4**. Despite representing only 6% of new vehicle sales, HDVs account for a staggering 47% of the freight sector's energy/fuel use. This highlights the importance of targeting HDVs in efforts to reduce emissions and transition to a more sustainable freight transportation system, due to them having the highest emissions and lowest vehicle numbers for all freight vehicle categories.

For targeting HDV emissions in Canada, certain provinces are more suitable for initial investigation due to their higher proportion of heavy-duty vehicles relative to their population, offering greater potential for emission reduction through HDV and infrastructure transitions. **Fig. 2.5** provides a per-thousand people breakdown of HDVs and MDVs across Canada and Canadian provinces, allowing for a simple comparison of provincial data against the federal average.

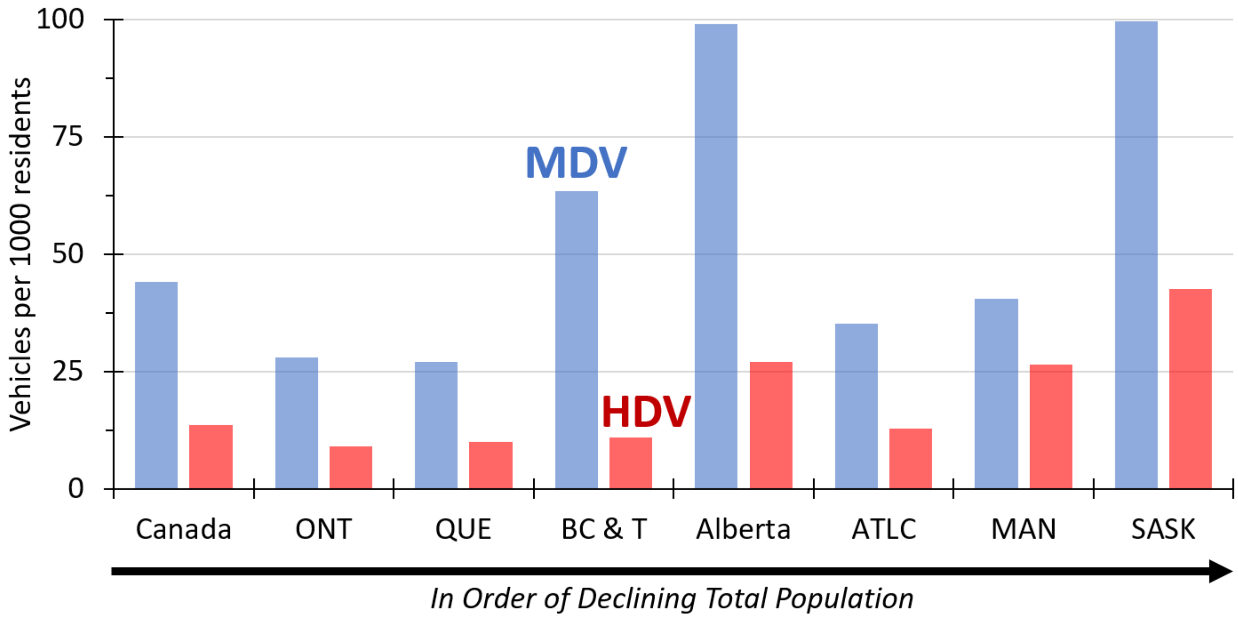



**Fig. 2.5.** Heavy-Duty (HDV) and Medium-Duty Vehicles (MDV) per 1000 People by Region for Canada.
*ONT is Ontario, QUE is Quebec, BC & T is British Columbia and Territories, ATLC is Atlantic Canada, MAN is Manitoba, and SASK is Saskatchewan. In order of declining total population from largest to smallest. Data taken from the Comprehensive Energy Use Database (Natural Resources Canada, 2023a), and Canadian population estimates (Statistics Canada, 2024a).*

**Fig. 2.5** illustrates that the Prairie provinces—Alberta, Saskatchewan, and Manitoba—have the highest proportions of heavy-duty vehicles in Canada, due to the industrial and agricultural nature of these provinces requiring substantial HDV usage. Although Saskatchewan has the highest proportion of heavy-duty vehicles, it has only 27% of Alberta's population, resulting in having less than half of Alberta's total heavy-duty vehicle population. With more than double the Canadian average for both heavy-duty and medium-duty vehicles, and having the largest population among the Prairie provinces, Alberta stands out as the heavy-duty freight capital of Canada.

Based on the factors discussed in this section, this investigation into the decarbonisation of freight transport in Canada will focus on the decarbonization of heavy-duty freight within the province of Alberta. This approach addresses both the largest emitting category of freight vehicles in Canada, and the province with the second highest proportion and population of these vehicles.

## 2.2 Towards Low GHG Emission Freight Using Internal Combustion Engines

The environmental impact of continuing with traditional diesel-powered ICE HDVs is significant, contributing to both local air quality issues and global climate change (Zalzal and Hatzopoulou, 2022). Reducing emissions and decarbonizing heavy-duty freight transport requires exploring the entire heavy-transport value chain, from the energy source, or 'well,' to the vehicle's operation, or 'wheel.' This includes the production and transportation of energy carriers, vehicle manufacturing, infrastructure development, and the logistics of fleet operations. Optimizing the entire chain is vital to reducing environmental impacts and enhancing the efficiency and reliability of low-GHG technologies (Khan et al., 2022), thus ensuring a proper transition to sustainable heavy-duty transportation.

The first step involves investigating the existing ICEV value chain and transitional ICEV technologies and fuels, which may play a crucial role in the transition to net-zero (NZ) GHG emissions for HDVs, but face challenges in fully transitioning to sustainable energy sources. Current heavy-duty vehicles use diesel-fueled internal combustion engines, operating by combusting diesel to produce mechanical power. Although this system is well-established with robust infrastructure, it relies on diesel and emits significant amounts of $CO_2$, methane, and NOx (Graham et al., 2008), the latter of which is produced by ICEVs regardless of fuel type, making it unsustainable for a net-zero future. Several transitionary and lower GHG emission fuels for HD-ICEVs have emerged within this space that aim to provide help in transitioning heavy-duty vehicles towards net-zero.

Synthetic fuels like biodiesel and renewable diesel are marketed to help reduce dependence on traditional fossil fuels. However, the low efficiency (around ~51%) associated with converting lignocellulosic biomass to biobased diesel (well-to-wheels efficiency of ~16%), and the distributed nature of the resources makes the fuel more expensive compared to the incumbent diesel energy system (Lof et al., 2019). Cost aside, producing biodiesel at a scale sufficient to meet Alberta's heavy-duty demand would require dedicating over 50% of the province's agricultural land to canola production (Layzell et al., 2020a), which is completely impractical for this industry, but could see use in smaller sectors like aviation.

Natural Gas (NG) is another alternative to diesel, currently used as compressed natural gas (CNG) in some vehicles like city buses but would most likely be as liquefied natural gas (LNG) for heavier-duty vehicles. While LNG would be the natural gas most appropriate for exploring long haul operations, like biodiesel, there are many issues with this fuel in the value chain. The higher cost of LNG compared to CNG, the limited range of LNG trucks relative to diesel HDVs, and the higher vehicle purchase price premiums create significant value chain challenges that make this transitional fuel too problematic to justify (Askin et al., 2015). Additionally, while natural gas theoretically produces lower $CO_2$ emissions than diesel during complete combustion, the release of new sources of natural gas along the entire HDV value chain in switching from diesel to natural gas has the potential to produce net climate damages rather than benefits in the years to come (Camuzeaux et al., 2015).

Plug-in Hybrid Electric Vehicles (PHEVs) combine electric powertrains with internal combustion engines, offering theoretically reduced emissions compared to conventional diesel vehicles. Due to the limited size available for these large on-board batteries, stringent weight and range requirements that come with HDVs, and necessity for fast refuelling, this technology is severely limited in its ability to impact emissions and reduce diesel usage. Despite the addition of larger batteries and electric compatibility, HD-PHEVs have shown emissions reductions of less than 5% in even some of the best-case scenarios (Hegde et al., 2023). Furthermore, their continued reliance on almost solely fossil fuels, and now plug-in technology as well, further complicates infrastructure requirements and still does not fully eliminate emissions, which makes them not ideal for a long-term or transitional solutions.

Low or net-zero GHG hydrogen fuel, used in tandem with diesel in a hydrogen diesel dual-fuel (HD2F) vehicle, provides a more viable transitional option for HDVs, now utilizing and supporting a potentially zero-emission energy source. HD2F vehicles can reduce carbon emissions by up to 40%, even with only 30–50% hydrogen usage (El Hannach et al., 2019). Additionally, the minimal conversion required to adapt existing trucks from diesel to dual-fuel mode, coupled with the negligible loss of efficiency, constitutes a major advantage of this technology compared to other available alternatives (Volvo Penta, 2023). Of course, they remain a transitionary technology as they cannot achieve full decarbonization from their use of diesel. Mention of HD2F leads to the consideration of pure hydrogen used in modified internal combustion engine vehicles, where hydrogen is ignited in a comparable manner to diesel. However, the current diesel port fuel injection engine configuration suffers many limitations for this application and limits the achievable load and efficiency for use with hydrogen. A potential solution is high-pressure hydrogen direct injection, but despite being a promising strategy, the low engine compression ratio of typical spark-ignition engines limits the thermodynamic efficiency and requires a solution like HD2F discussed previously to make up for the loss (Yip et al., 2019). This technology is advancing rapidly however, and some modeling shows potential for future use (HPDI Technology, 2024).

Within all these transitional fuel options for ICEs, the common factor that is limiting the shift to low-GHG emissions rather than net-zero GHG emissions, is the internal combustion engine itself. This means that to achieve a proper transition to zero-emission heavy freight, it will require both a zero-emission drivetrain for HDVs and zero-emission fuels to power it.

## 2.3 Towards Net-Zero GHG Emission Freight Using Electric Drive Trains

To eliminate the inherent emissions of internal combustion engines, a new type of zero-emission vehicle is needed to power HDVs without generating greenhouse gases. Only two solutions are currently in production and have government/industry support for the heavy-duty sector, these being Hydrogen Fuel Cell Electric Vehicles (FCEVs) and Battery Electric Vehicles (BEVs). At the core of both technologies, is the use of electricity to propel an onboard electric traction motor, with the difference between these technologies being where this electricity is sourced from.

In fuel-cell electric drivetrain systems, the integrated hydrogen fuel-cell stack generates electricity from on-board stored hydrogen (**Fig. 2.6**) to either power the electric drive train directly, or to charge an intermediate battery, which covers peak loads during acceleration and recovers energy during braking. In contrast, battery electric drivetrain systems store energy entirely within a much larger onboard battery, which is charged from an external power source rather than an on-board fuel source. For both drivetrain technologies, it is crucial to produce low to zero greenhouse gas electricity—whether directly for BEV batteries or through low GHG emission hydrogen for FCEV batteries—to ensure the entire value chain supports a net-zero emission profile.

To determine which technology is best suited for supporting heavy-duty freight in Alberta, it is essential to understand the use cases and limitations of each, to assess whether one or both are optimal for this transition.

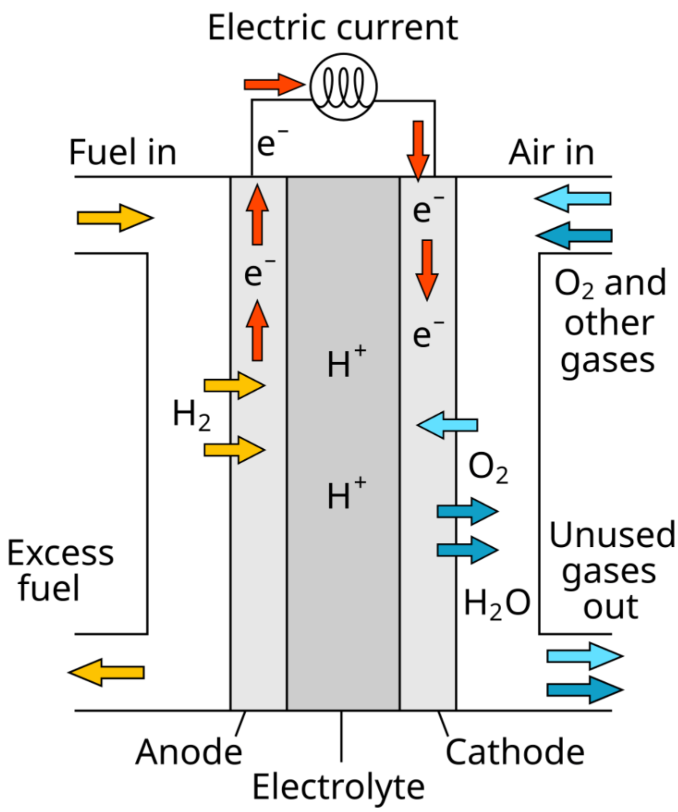



**Fig. 2.6.** How Hydrogen Fuel Cells Can Convert Hydrogen Gas to Electricity and Water with Zero Emissions.
*By R. Dervisoglu – sourced from (Dervisoglu, 2012).*

Battery electric heavy-duty vehicles are generally well-suited for short-haul (SH), return-to-base operations, similar to electric cars. This setup supports at-base charging during shift changes and overnight, without compromising daytime hauling and short-range operations (Forrest et al., 2020). BEVs perform well in this sort of smaller-scale operational settings (Anselma and Belingardi, 2022), however, this advantage is greatly reduced with larger fleets, multiple off-site driver shifts (Hunter et al., 2021), or 500+ kilometre trips (Burke et al., 2023). Although advancements in battery electric technology are anticipated, such as faster charging speeds with megawatt chargers and the broader integration of fast charging across the region, these improvements do not yet bring them on par with incumbent long-haul diesel internal combustion engines (Schneider et al., 2023).

Because of this, BEVs pose challenges for long-haul (LH) operations, where LH-HDVs need to carry heavy loads up to 63.5 t GVW, face stringent weight restrictions complicated by heavy batteries, require extended ranges of 500 to 1200 km per day, and rely on rapid refuelling for prolonged operation. Some solutions to these challenges exist, such as using a catenary system to provide continuous charging for LH BEVs. However, BEVs equipped with catenary systems require extensive road infrastructure modifications, which are extremely cost-prohibitive and logistically complex, and demand long-term investments in overhead power lines along major transport routes (Rohith et al., 2023). For these reasons, battery electric vehicles are a highly viable option for shorter-haul operations within the heavy-duty vehicle sector. However, a more effective solution is needed to address the challenges posed by the more restrictive, and larger sector of long-haul HDV operations.

Hydrogen fuel cell electric vehicles are emerging as the most promising zero-emission option for HDVs in the long-haul market, due to their operational similarities to long-haul ICEVs including rapid refuelling, longer range potential, and lower weight compared to range-equivalent BEVs. (Burke, 2020; Burke et al., 2023; Cunanan et al., 2021). The major challenge with implementing FCEVs for long-haul, is the simultaneous need to produce vehicles that meet the demands of the freight sector, while also building an entirely new value chain to support FCEVs including the production, transport, and delivery of fuel cell-grade hydrogen via refuelling stations (Lajevardi et al., 2022). Canada accounts for a very small fraction of existing FCEV vehicles and stations, and only a few stations have been deployed to support heavy-duty vehicles (Samsun et al., 2022).

To address the 'chicken and egg' challenge of hydrogen and ZEV vehicle/infrastructure deployment, the Canadian and Alberta Governments have introduced incentive programs such as the Incentives for Medium- and Heavy-Duty Zero-Emission Vehicles (iMHZEV) Program to build both hydrogen fuelling stations (Alberta Innovates, 2023; Emissions Reduction Alberta, 2024), and to deploy $H_2$ FCEVs and BEVs (Emissions Reduction Alberta, 2023; Transport Canada, 2022a). While the current cost of heavy-duty BEV and FCEV vehicles is currently much higher than the incumbent diesel vehicles, as production volumes increase and manufacturing costs decrease, there are expectations that they should reach cost parity with diesel within the next 10-12 years (Burke et al., 2023; Burnham et al., 2021; Cunanan et al., 2021). However, these higher initial costs currently associated with hydrogen production, and the lack of widespread infrastructure for ZEVs provide a large barrier to entry for Canada and Alberta.

For this thesis, hydrogen fuel cell electric vehicles and battery electric vehicles are chosen as the primary zero-emission alternatives for transitioning Alberta's heavy-duty vehicle sector to net-zero emissions. The choice is driven by each technology's distinct operational strengths: FCEVs are well-suited for long-haul applications, offering extended range, rapid refuelling, and a lighter weight compared to BEVs, making them a promising option for Alberta's demanding LH-HDV sector. BEVs, meanwhile, are optimal for short-haul routes such as urban and return-to-base operations, where regular charging intervals do not impact cargo capacity or operational efficiency. As well, both technologies align with Canada's iMHZEV program, which identifies BEVs and FCEVs as primary pathways for achieving net-zero HDVs.

While Plug-in Hybrid Electric Vehicles (PHEVs) are considered a zero-emission option by Transportation Canada (Transport Canada, 2022a), the program states that "A ZEV is a vehicle that has the potential to produce no tailpipe emissions. They can still have a conventional internal combustion engine but must also be able to operate without using it." This statement is primarily relevant to MDVs, however for heavy-duty vehicles, PHEVs can currently provide minimal emissions reductions of less than 5% even in optimal scenarios (Hegde et al., 2023) and continue to rely heavily on fossil fuels. Their limited battery capacity, inability to sustain fully electric operation over long distances, and complex infrastructure requirements ultimately make PHEVs unsuitable as a true ZEV option for Alberta's HDV sector.

While FCEVs and BEVs represent the most impactful solution for decarbonizing Alberta's HDV sector, both still face challenges due to their limited availability, especially high-GVW models that are still under development and necessary for LH operations (Natural Resources Canada, 2022) and lack of a mature value chain overall. However, this strategic focus on FCEVs for LH routes and BEVs for SH operations is well-aligned with the operational requirements of the freight sector despite these infrastructural and economic hurdles, and offers the most viable pathway to a sustainable, low-emission future for Alberta's HDV industry.

## 2.4 Production of Low GHG Hydrogen

In the transition to net-zero, producing low-GHG and ultimately zero-GHG hydrogen to support FCEVs is just as essential as converting heavy-duty ICE vehicles to FCEVs. This dual focus helps avoid the 'chicken and egg' problem common in this field, where both technologies depend on the other to be fully effective. Hydrogen is a versatile energy carrier that can be produced either from fossil fuels or electricity via electrolysis of water. Towards this, hydrogen production is often categorized by colour codes, with each colour representing a different production method and primarily reflecting its associated environmental impact. The three main methods of hydrogen production used today are grey, which generates the most GHG emissions; blue, which reduces emissions from grey hydrogen by incorporating carbon capture and storage (CCS); and green, which is nearly emission-free and produced using renewable energy. In Alberta, hydrogen is primarily produced as an industrial feedstock, with approximately 80% of production in 2023 coming from grey hydrogen, and the other 20% from blue hydrogen (Alberta Energy Regulator, 2024a).

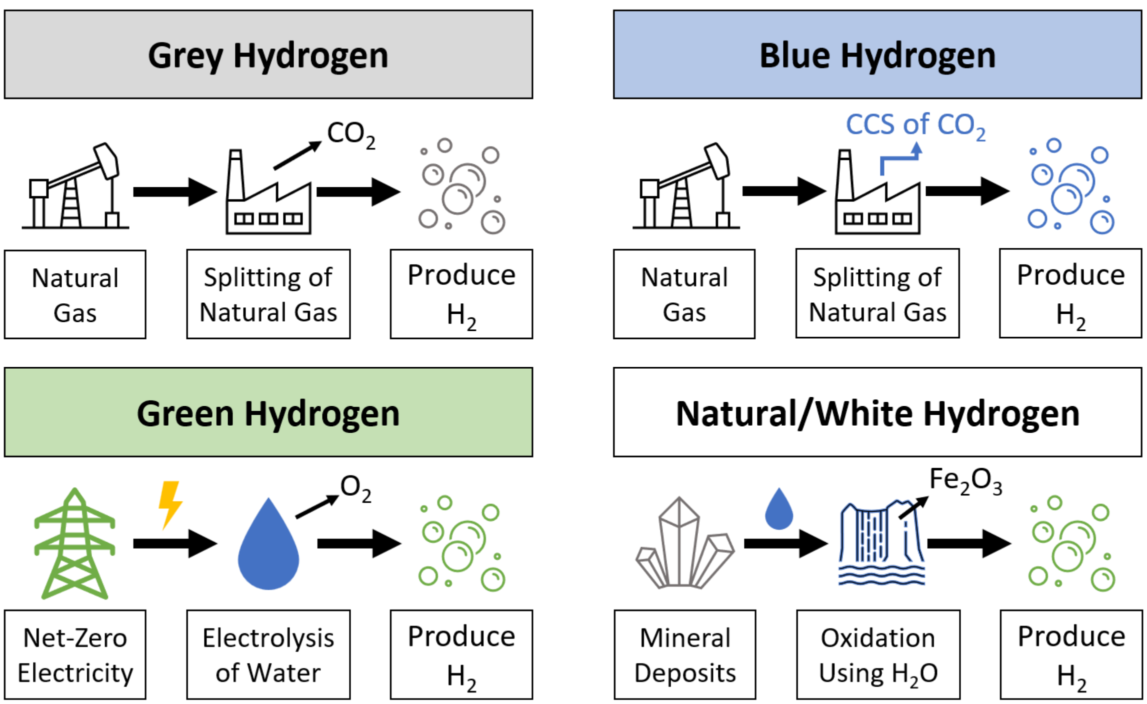



**Fig. 2.7.** Four Primary Methods for Hydrogen Production in Canada and Globally.
*CCS for blue hydrogen refers to the carbon capture and storage of $CO_2$, Iron oxide ($Fe_2O_3$) in natural hydrogen is an example of an oxidation product, not the only one that can be created/used.*

Grey hydrogen is most common form of hydrogen production, making up approximately 98% of global hydrogen production in 2020 (International Energy Agency, 2020). Natural gas accounts for about 75% of this grey hydrogen production and is converted to hydrogen using three primary technologies. The most widely used method is Steam Methane Reforming (SMR), which utilizes high-temperature steam both as an oxidant and as a source of hydrogen. SMR is highly efficient in hydrogen production but results in significant $CO_2$ emissions (Navas-Anguita et al., 2021). The other two, less commonly used technologies are Partial Oxidation (POx), which uses oxygen or air as the oxidant, and Autothermal Reforming (ATR), a process that combines elements of both SMR and POx. Aside from natural gas, coal is the other major fuel source for hydrogen production worldwide, largely due to its dominant role in China's chemical and steel industries. Approximately 23% of global hydrogen production is based on coal, primarily using the process of gasification (International Energy Agency, 2020). In this process, an oxidant (such as oxygen, air, steam, $CO_2$, or combinations thereof) reacts at high temperature with coal to produce syngas. This syngas is similar to that produced from natural gas-based routes but typically has a much lower hydrogen content then what is produced from SMR or ATR.

Blue hydrogen addresses the significant emission issues associated with grey hydrogen production, using the same natural gas production methods but incorporating carbon capture and storage within this. Only about 1% of global hydrogen production from fossil fuels includes CCS (International Energy Agency, 2020), indicating that CCS within this technology is still relatively novel. Among the three technologies previously described, while SMR is highly efficient for grey hydrogen production, ATR (a combination of SMR and POx) is generally more favorable due to easier CCS due to its integrated design, and when considering both cost and emissions overall (Oni et al., 2022). This method of ATR hydrogen production with CCS results in some of the lowest life cycle greenhouse gas (GHG) emissions of blue hydrogen production, reducing emissions by upwards of 90% from grey hydrogen. However, this comes with an increase in hydrogen production costs with ATR CCS ranging from a 20% to 35% increase in cost, and SMR CCS being upwards of 45% or more. (Oni et al., 2022). Although adding CCS to blue hydrogen increases costs compared to traditional grey hydrogen, meeting global emission reduction standards will make this additional cost a necessary part of hydrogen production. Therefore, reducing the cost of CCS will be a critical area of future research.

Green hydrogen is produced via water electrolysis using electricity preferably sourced from renewable energy, representing the most environmentally promising method as it emits virtually no greenhouse gases during production. Green hydrogen is still considered 'near net-zero GHG' however, with the term 'near' used because the production and maintenance of green energy infrastructure—such as solar panels, wind turbines, and electrolyzers—may involve some GHG emissions. As well for regions like Alberta, electricity generation is approximately 16% renewable, with the majority of power generated from fossil fuels (Environment and Climate Change Canada, 2023). This reliance on non-renewable energy sources could diminish the environmental benefits of green hydrogen production, particularly if the energy used comes from high-emission sources like in Alberta. While representing a promising method of future hydrogen production, the scalability of green hydrogen is currently constrained by the availability and cost of renewable energy sources and electrolyzer technologies, and current green hydrogen production can be upwards of three to four times more expensive than blue in Alberta (Khan et al., 2022).

There are various other colors categorized under the umbrella of green hydrogen as well (despite the confusion this may cause based on the intention of colours representing different production method) such as pink and yellow hydrogen. These are all produced via electrolysis as is green hydrogen, but differ based on the source of renewable electricity, with pink hydrogen using nuclear power and yellow hydrogen using solar energy. These offer benefits as the key cost-determinant of green hydrogen is the price of renewable electricity, and reducing that cost through cheaper renewable sources provides a great benefit (Khan et al., 2022).

Natural hydrogen, often referred to as white hydrogen, has recently emerged as a promising alternative to mitigate some of the drawbacks associated with green hydrogen production. Early exploration projects, such as the Rider Natural Hydrogen Project in Saskatchewan, have revealed hydrogen concentrations exceeding 10% in seven out of 45 wells, with the other wells showing ranges between 1-10%, and a maximum of 96.4% hydrogen (Edward Laity, 2024). Additionally, new data from Quebec suggests potential hydrogen reserves in the region, with the first reports highlighting this resource's emerging potential (INRS, 2024). Similar discoveries in the United States have indicated vast stores of natural hydrogen that could serve as a carbon-free energy source (Pearce and Yale, 2024). Globally, the potential of natural hydrogen is generating interest, as this resource may represent a more sustainable and cost-effective path to decarbonization.

Scientific research has begun to explore the fundamentals, promise, and problems of this emerging resource, with recent studies discussing its potential to revolutionize the energy landscape (Blay-Roger et al., 2024; Gallagher, 2023). Although natural hydrogen remains relatively underexplored, the findings suggest it could play a crucial role in the future energy transition, particularly in regions like Alberta and Saskatchewan.

There are other production methods as well such as turquoise hydrogen, produced via methane pyrolysis which generates solid carbon instead of $CO_2$. Production of hydrogen from biomass with CCS is also possible, although it would compete with other sources of demand for biomass as explained previously. However, these technologies remain in the early stages of development and are not yet commercially viable, thus are not considered major production methods (Korányi et al., 2022).

In the Canadian context, particularly in Alberta, there is a unique opportunity to advance the hydrogen economy due to the province's substantial natural gas resources, which can render SMR and ATR processes economically attractive. The Government of Alberta, through initiatives like Emissions Reduction Alberta (ERA) and Alberta Innovates (Alberta Innovates, 2024), has committed significant funding towards hydrogen projects, essential for overcoming the higher costs associated with transitioning to low GHG hydrogen production.

Regulatory frameworks and government incentives are pivotal in shaping the hydrogen market. Policies that support infrastructure development, research, and the adoption of hydrogen technologies are vital for creating a sustainable market. Furthermore, Alberta's strategic management of its natural resources not only supports national energy goals but also positions the province as a leader in the global hydrogen market (Government of Alberta, 2021a).

## 2.5 Transport and Delivery of Hydrogen for FCEVs

The transport and delivery of hydrogen is a complex aspect of the value chain due to the wide variety of states in which hydrogen can be transported, the different storage technologies, the various transport methods, and the delivery processes to vehicles at refuelling stations. While this variety may seem beneficial for expanding hydrogen use cases, the lack of consensus on the optimal processes for industry creates significant challenges for the rapid growth of commercialization and may lead to compatibility issues throughout the value chain. Addressing these concerns will therefore be a critical part of ensuring a smooth hydrogen transition across the entire value chain.

Unlike diesel and gasoline, which are distributed and used almost exclusively in liquid form, hydrogen's natural state as a gas offers much greater variety for how it can be stored and used. This is why diesel and gasoline are typically quantified by volume, whereas hydrogen is quantified by weight. The volume of hydrogen does not accurately reflect its quantity because it varies significantly depending on its pressure and state. This variability makes the pressure at which hydrogen is stored in HDV tanks and supplied by fuelling stations critical for long-haul trucking. The more hydrogen that can be stored in a smaller space, the better it supports the extended range required for long-distance travel. Hydrogen is commonly kept in four states and pressures for commercials use:

- 20-70 Bar (Low-Pressure Gas): Compressing hydrogen to 20-70 bar is relatively straightforward, as it involves low-pressure compression using standard industrial compressors. However, it requires unreasonably large storage volumes to hold significant amounts of gas, making it only suitable for situations where space is not a concern, such as with long-distance pipeline transport. One low-pressure storage solution may be salt caverns, used for large-scale hydrogen storage by injecting hydrogen into hollowed-out formations at depths of 500 to 1,500 metres, providing a secure and flexible environment for efficient hydrogen injection and withdrawal up to higher pressures of 100-200 bar (Reichwein, 2022).
- 350-700 Bar (High-Pressure Gas): Compressing hydrogen to pressures as high as 700 bar requires more advanced and powerful compression systems, but it is essential for transporting reasonable quantities of hydrogen efficiently. At these high pressures, hydrogen storage solutions must be robust and capable of withstanding the significant forces involved, typically requiring specialized high-pressure storage tanks. While 350 bar hydrogen may see use in short range applications, 700 bar hydrogen is more optimal for LH FCEVs, as the higher pressure allows for a greater amount of hydrogen to be stored, thereby extending the vehicle's range capabilities (Shin and Ha, 2023).
- Liquid Hydrogen ($LH_2$): $LH_2$ represents the most challenging state for hydrogen storage, requiring cooling to cryogenic temperatures (below -253°C) and specialized insulated tanks to maintain this state. This energy-intensive and costly liquefaction process results in efficiency

losses but allows for higher energy density, making $LH_2$ suitable for high-energy-demand applications such as aerospace and potentially heavy-duty transport. Long-term storage is difficult however, as liquid hydrogen tends to boil off after extended periods in storage. The lower transportation costs per unit compared to compressed hydrogen could see remote delivery benefits, or further range improvements for FCEVs (Khan et al., 2022).

Understanding the desired pressures and states for hydrogen allows for the development of proper storage technologies that can handle the challenges that come with these. For detailed standards, ISO 19881 and ISO 19882 (ISO, 2018a, 2018b) are the primary international standards covering the design, construction, and testing of composite and metallic hydrogen cylinders.

These standards define four main types of hydrogen storage tanks. Type I tanks are made entirely of metal and are used primarily for stationary storage or low-pressure applications like 20 bar hydrogen pipelines. Type II tanks feature a metal liner wrapped in composite material, making them lighter and more suited for medium-pressure hydrogen storage, typically at 350 bar. Type III tanks have a composite liner with a metal wrap, allowing them to store hydrogen at higher pressures, around 350 to 700 bar, which is commonly used in compressed hydrogen applications. Finally, Type IV tanks are fully composite, with no metal components, making them the lightest option and ideal for storing hydrogen at very high pressures, such as 700 bar, which is often used in fuel cell electric vehicles to maximize driving range (ISO, 2018a, 2018b).

With hydrogen stored and ready to transport, three main delivery methods emerge for use in urban settings. The first is liquid hydrogen delivery via trucks, which offers a solution for higher-capacity transport over longer distances. Hydrogen is first liquefied, and transported in specialized insulated trucks that can hold around 3.6 tonnes of liquid hydrogen. This method provides greater energy density and lower transportation costs per unit compared to compressed hydrogen, but it involves significant energy consumption and costs related to the liquefaction process as well (Khan et al., 2022). Compressed hydrogen delivery via tube trailer trucks provides a more reasonable solution for gaseous hydrogen delivery. This method involves transporting hydrogen at high pressures typically between 350-700 bar and can carry up to a tonne of hydrogen at 500 bar, making them suitable for shorter distances and initial market development. However, this method is limited by the lower capacity of each truck and higher transportation costs per unit of hydrogen compared to pipelines. Delivering compressed hydrogen via pipelines, typically at pressures of 20 to 70 bar, is the most efficient method for transporting large quantities of hydrogen, ranging from 100 to 300 tonnes per day depending on the pipeline's length and diameter. This method is ideal for long-distance transport and large-scale hydrogen distribution networks, but requires substantial upfront investments in infrastructure and ongoing maintenance to prevent degradation (Mahajan et al., 2022).

In addition to the three primary methods of hydrogen transport, alternative technologies are also available for more niche circumstances. Liquid Organic Hydrogen Carriers (LOHCs) can store hydrogen chemically bonded to a carrier such as methanol (liquid at ambient conditions), where methanol reformers can convert it back into hydrogen on-site. Methanol provides easier handling and transportation compared to gaseous/liquid hydrogen and enables transport using existing fuel infrastructure. While offering potential to reduce GHG emissions by greater than 45% compared to diesel, the technology and infrastructure are still mainly under development and not available for widespread commercial use (Azolla Hydrogen Ltd., 2023).

Ammonia ($NH_3$) offers another viable alternative, particularly for large-scale and global hydrogen distribution. Ammonia can store hydrogen at a higher density than other carriers and benefits from existing infrastructure already in place due to its widespread use in the chemical industry. This makes it a promising candidate for long-distance hydrogen transport. However, ammonia requires a process known as cracking to release hydrogen at the point of use ($2NH_3 \rightarrow 3H_2 + N_2$), which introduces energy losses and adds complexity to the supply chain. Despite this drawback, ammonia's ease of transport and established logistics make it a strong contender for global hydrogen distribution, and has seen some initial development with HDVs using in-vehicle ammonia crackers integrated with hydrogen fuel cells (AMOGY Inc., 2024).

With hydrogen now delivered to stations, the ultimate step is delivering hydrogen to the FCEVs. Refuelling stations typically provide two output pressures for vehicles, 350 bar and 700 bar, requiring station pressures of 900 bar or higher to ensure efficient refuelling at these levels. There are some inherent challenges with storing hydrogen on-board; the ~60 kg (or more) of fuel required for LH trucking would take up 1.4 $m^3$ of space when pressurized to 700 bar, or 2.4 $m^3$ for 350 bar (Lof et al., 2019). Higher pressure of course allows these vehicles to travel greater distances between refueling stops. While less commercially available, long-haul heavy-duty vehicles often use 700 bar hydrogen storage, which provides the higher energy density necessary for longer ranges. 350 bar refuelling is more commonly used for buses and light freight. This lower pressure is sufficient for larger storage tanks and is easier to achieve, making it the standard for many commercial applications. As of now, liquid hydrogen is mostly used in specific industrial applications and aerospace, rather than in mainstream vehicle refueling due to the complexities and costs associated with storing and handling $LH_2$.

# 3. Net-Zero Transition Model of Alberta's Heavy-Duty Trucking Sector

This chapter has been submitted as an article to *Transportation Research Part D: Transport and Environment* and is currently under review. The content presented in this chapter reflects the findings and methodologies that are being evaluated by the journal's peer-review process.

## 3.1. Introduction

To address the growing threats of climate change, dozens of nations, including Canada, have committed to achieve net-zero greenhouse gas (GHG) emissions by 2050 (Government of Canada, 2021; Lang, 2023). Heavy-duty vehicles (i.e. Class 8, 15 to 63.5 tonnes gross vehicle weight (GVW)) account for 5.3% of Canada's greenhouse gas emissions, equivalent to 35 Mt $CO_2e$/year (Environment and Climate Change Canada, 2023). To decarbonize heavy-duty vehicles (HDV), the Canadian government has set a target of 35% of new HDV sales to be zero-emission vehicles (ZEVs) by 2030, with a further target of near 100% by 2040. (Environment and Climate Change Canada, 2022a).

The heavy loads, the need for rapid refuelling, and the long distances (average 86,900 km/veh/yr) travelled by the 489,000 Class 8 trucks in Canada in 2019 make this sector particularly challenging to decarbonize. This is especially the case in the province of Alberta, which in 2019 had 23% of all HDVs in Canada despite having only ~12% of the Canadian population (Natural Resources Canada, 2023a).

The ZEV choices for new HDV sales include battery electric vehicles (BEV) and hydrogen fuel cell electric vehicles (FCEV), as well as the transitionary non-zero emission plug-in hybrid electric vehicles (Natural Resources Canada, 2023b). Compared to diesel-fuelled internal combustion engine vehicles (ICEV), BEVs have at least twice the efficiency in converting their supplied energy to vehicle kilometers travelled (Alonso-Villar et al., 2022; Forrest et al., 2020; Gray et al., 2022; Mareev et al., 2017; Peters et al., 2021) due to factors like efficient electric motors and the ability to use regenerative braking. Also, with fewer moving parts, the maintenance cost of BEVs is expected to be lower than for ICEVs. However, there are a number of challenges facing the large scale deployment of BEVs in the heavy-duty vehicle market (Cunanan et al., 2021), including (a) heavy loads and long travel distances requiring battery weights that compromise the commercial loads that can be carried, (b) the time required to recharge batteries, especially for long-haul markets, and (c) the impact of low temperatures on vehicle range and recharging requirements.

These constraints have increased interest in heavy-duty FCEVs, where the energy is stored on-board as hydrogen that is converted to electricity to supply both the motors driving the wheels, and a much smaller bank of on-board batteries (Cullen et al., 2021; Li et al., 2022a; Pardhi et al., 2022). Therefore, for long distance and heavy loads, FCEVs promise lighter vehicle weights, longer ranges between refuelling, more rapid refuelling, and better winter performance than the BEV alternatives.

In the transition of heavy-duty (HD) road transport to net-zero, there is likely to be a role for both BEV and FCEVs with the BEVs dominating the short-haul markets and the FCEVs dominating the long-haul. These market separations are complicated by the fact that many companies serving the long-haul markets buy new vehicles and use them for more than 200,000 km/vehicle/yr for the first 4 to 5 years, but then sell them into the short-haul market where their annual vehicle use is much lower (Alberta Motor Transport Association, personal communication, 2023).

The heavy-duty BEV and FCEVs are still in the initial stages of deployment in terms of vehicle availability, recharging/fuelling infrastructure, and support for maintenance and operations. To meet the government targets, it will be essential to coordinate the deployment of the vehicles and infrastructure in a way that meets the needs of the sector.

The primary objective of this chapter is to understand the requirements and feasibility of a net-zero transition in Alberta on HDV sales, low GHG energy supply, and ZEV fuelling/recharging infrastructure. The work seeks to contribute to the literature regarding the challenges and opportunities associated with creating new, zero-emission value chains, and in doing so, inform policy and investment decisions by both government and industry working to achieve net-zero objectives.

Most previous studies focused on specific elements of this transition such as the scale needed for low GHG hydrogen production (Ahmadi and Kjeang, 2015), the design and costs of hydrogen fuelling stations (Argonne National Laboratory, 2017), the efficiency, performance, and cost of hydrogen-fuelled vehicles (Pardhi et al., 2022).

This study explores the scale and logistical challenges of building the whole value chain; the economic issues will be considered in a subsequent study.

## 3.2. Literature Review

### 3.2.1. The Net-Zero Transition and Options for Heavy-Duty Trucking

In the desire to decarbonize the heavy trucking industry, fuel switching to compressed or liquefied natural gas has the potential to achieve only marginal reductions in GHG emissions. Renewable diesel or natural gas are theoretically possible to achieve more substantial emission reductions, but limitations in feedstock availability and costs reduce their viability as net-zero solutions for the trucking sector (Sen et al., 2017).

To achieve net-zero GHG emissions, heavy-duty vehicles require zero-emission energy carriers, such as electricity or hydrogen, and when they are coupled to an electric drivetrain, major efficiency improvements can be achieved in converting the energy carrier to kilometres travelled when compared to diesel-fuelled internal combustion engines (Anselma and Belingardi, 2022; Cullen et al., 2021).

Also, battery electric, or fuel cell electric drivetrains have fewer moving parts than internal combustion engines, promising lower maintenance and repair costs per kilometre, and potentially a longer vehicle life than the incumbent diesel ICE vehicles (Alonso-Villar et al., 2022; Burke et al., 2023; Hunter et al., 2021).

Battery electric vehicles in the heavy-duty freight sector are well suited to short haul (SH), return-to-base operations (ideally driving less than 200 km/day), thereby allowing overnight charging, and on-board battery storage that does not compromise hauling capacity (Forrest et al., 2020). From the perspective of total cost of ownership, BEVs perform well in smaller-scale operational settings (Anselma and Belingardi, 2022). However, this advantage is reduced with larger fleets, multiple driver shifts (Hunter et al., 2021), or journeys exceeding the 500-kilometres (Burke et al., 2023). Consequently, BEVs are a challenging zero-emission solution for long-haul (LH) operations, where vehicles carry heavy loads (up to 63 t GVW) for 500 to 1200 km/day and so they require rapid refuelling since the driver's time is a significant contribution to the total cost of vehicle ownership.

For the LH market, hydrogen-FCEVs have been gaining profile as the most promising zero-emission heavy-duty vehicle since they allow rapid refuelling and lower weights than a range-equivalent BEV (Burke, 2020; Burke et al., 2023; Cunanan et al., 2021). LH ICE vehicles are frequently driven over 200,000 km per year for the first four to five years of their lives, and then sold into the SH market where their annual vehicle kilometres travelled (VKT) is much lower (Alberta Motor Transport Association, personal communication). If this business practice continues in the transition to zero-emission vehicles, many FCEVs are likely to appear in the SH market.

A major challenge with FCEVs is the need to not only produce vehicles that can meet the needs of the freight sector, but simultaneously build an entirely new value chain, including the production, transport and delivery of fuel cell grade hydrogen (Lajevardi et al., 2022). Others have expressed concerns with the cost of hydrogen production from water electrolysis with renewable electricity (Burnham et al., 2021), but lower cost, low GHG hydrogen could be produced from natural gas coupled to $CO_2$ capture and geological storage (CCS) in regions like Alberta (Lof and Layzell, 2019). In Alberta, more than 5000 t $H_2$/day is currently produced at low cost (about CAD 1/kg $H_2$) for use as an industrial feedstock. While this hydrogen has significant life cycle emissions (about 12 t $CO_2$/t $H_2$, (Romano et al., 2022)), the production process can be modified (Ahmadi and Kjeang, 2015; McKenzie et al., 2023) to dramatically reduce GHG emissions using CCS and produced low GHG $H_2$ for less than CAD 2/kg $H_2$ (Layzell et al., 2020c; Meikle et al., 2024). If used as an energy carrier, this hydrogen could accelerate the transition to zero-emission, heavy-duty vehicles.

As of 2022, more than 50,000 FCEVs were on the road around the world, supported by over 700 hydrogen refuelling stations (Samsun et al., 2022). Canada accounts for a very small fraction of these vehicles and stations and only in the past two years have a few stations been deployed to support heavy-duty vehicles. To address this challenge, the Canadian and Alberta governments have introduced incentive programs to produce low GHG hydrogen (Department of Finance Canada, 2021; Kpekou et al., 2024), to build hydrogen fuelling stations (Alberta Innovates, 2023; Emissions Reduction Alberta, 2024), and to deploy $H_2$ FCEVs (Emissions

Reduction Alberta, 2023; Transport Canada, 2022a). Similar initiatives are being deployed in other nations (Astiaso Garcia, 2017; Lajevardi et al., 2022; Li et al., 2022b).

While the current cost of heavy-duty FCEV vehicles is currently much higher than the incumbent diesel vehicles, as production volumes increase and manufacturing costs decrease, there are expectations that FCEVs should reach cost parity with diesel within the next 10-12 years (Burke et al., 2023; Burnham et al., 2021; Cunanan et al., 2021).

### 3.2.2. Modelling Transformative Change

Technological transitions typically occur as 'S' Curves where small, gradual increases in market share are followed by exponential growth to reach an inflection point at about 50% market share following which the growth market share growth declines as the market becomes saturated (Marchetti, 1991). **Eq. (1)** can be used to define the S curve:

$$\boldsymbol{MS(t) = \frac{M}{1+e^{-b(t-t_{50})}}} \quad \textbf{(1)}$$

where **MS(t)** is the percent market share claimed by the new technology at year '**t**', **M** is the total market share (typically 100%), **b** is the growth rate (typical values between 0.2 and 1.0), and $\mathbf{t_{50}}$ is the year when 50% of the total market share has transitioned to the new technology.

'S' curves have been used to describe the adoption of new technologies from mobile phones (Boretos, 2007), New Energy Passenger Vehicles (Li et al., 2020), Digital Cameras (Woo and Magee, 2022), and other household tech (Hipkins and Cowie, 2016; Marchetti, 1991). In addition, **Eq. (1)** can be used with negative values for growth rate (b) and calculate decline rates with time.

### 3.2.3 Infrastructure Needs to Support ZEV Deployment

Incumbent systems for refuelling heavy-duty vehicles include a combination of public-facing truck fuelling stations, and private, behind-the-fence refuelling systems (Personal Communications, Alberta Motor Transport Association). In the transition to battery-electric vehicles, the requirement for long recharging times is likely to support a shift to more private refuelling operations. However, current price projections for hydrogen fuelling stations (Argonne National Laboratory, 2017), and the importance of scale in minimizing the cost of hydrogen transport and delivery (Ahmadi and Kjeang, 2015), suggests that the transition to hydrogen-FCEVS will probably support a shift to larger, more public facing fuelling stations.

The incumbent diesel refuelling system can be used to put the scale of the refuelling challenge in perspective. In 2019, the 111,415 heavy-duty vehicles in Alberta consumed about 3.1 billion litres of diesel (Natural Resources Canada, 2023a), resulting in an average of 27,450 L/vehicle/yr. Assuming the 'average' HD vehicle refuels every other day (i.e. 182.5 days/y), each refuelling requires an average of 150 L diesel (5.8 $GJ_{hhv}$), so the energy-equivalent hydrogen requirement would be 41 kg $H_2$ per refuelling.

Assuming a 'typical' diesel refuelling station serves an average of 200 refuels per day. The province would require 279 stations each providing an average of 30,082 L/day. Therefore, the energy-equivalent hydrogen requirement would need stations delivering an average of 8.2 t $H_2$/day. Note that the demand for hydrogen would be less since FCEVs are more efficient in converting chemical energy into km traveled than ICE vehicles (Hunter et al., 2021). On the other hand, in a net zero future, many public-facing stations could be significantly larger than 8 t $H_2$/day and serve hundreds of trucks per day.

It is worth noting that the dominant model for designing and costing hydrogen fuelling stations (Argonne National Laboratory, 2017) only allows for station sizes up to 10 t $H_2$ /day. The hydrogen supply to the stations is assumed to be either as compressed gas (either in pipeline or as compressed gas or as liquid nitrogen), and the vehicles receive hydrogen gas at either 350 bar or 700 bar. However, recently there has been a lot of interest in on-board liquid hydrogen storage to increase the storage capacity and range for these vehicles so they are more similar in performance to the incumbent ICE vehicles (Ahluwalia et al., 2023; Daimler Truck, 2024). Development and deployment of on-board liquid hydrogen could have significant impact on the cost and deployment strategy for heavy-duty FCEV vehicles.

## 3.3 Research Methodology

### 3.3.1 Model Overview

Data from government sources (Natural Resources Canada, 2023a; Statistics Canada, 2010) were obtained for Alberta, Canada's heavy-duty (HD, Class 8, 15+ t GVW) truck sales, registered vehicles, average vehicle kilometres traveled by registered vehicles with vehicle age, and total fuel use per year between 1981 and 2019. The data were used to build a computer model to explore a variety of scenarios for the future of Alberta's heavy-duty trucking sector, and to determine what is required to achieve Canada's net-zero targets.

The model consists of three modules (**Fig. 3.1**): a stock and flow module, a vehicle kilometres travelled (VKT) module and a module that calculates energy carrier demand and GHG emissions. Therefore, assumed changes in market share of HDV sales (**Fig. 3.1C**) are used to calculate vehicle registrations, VKT/yr, energy demand and GHG emissions. Using **Eq. (1)**, an 'S'-curve relationship was used to project ZEV market share from 2020 to 2050. In this way, the model can be used to generate a wide range of scenario projections for the future of the HD trucking sector in Alberta.

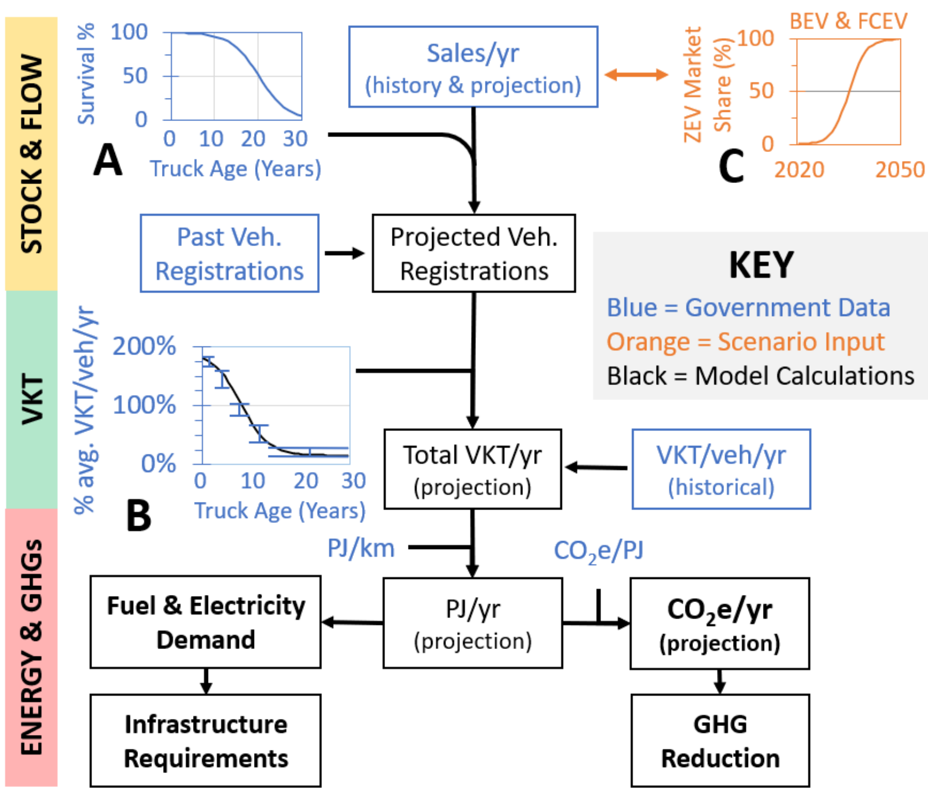



**Fig. 3.1.** Overview of the Model Design.
*Design includes a stock and flow module, a VKT module, and a module that calculates energy carrier demand and greenhouse gas (GHG) emissions. BEV, battery electric vehicle; FCEV, fuel cell electric vehicle; PJ, petajoule (higher heat value); VKT, vehicle kilometres traveled.*

### 3.3.2 Model Structure

Historical data on heavy-duty vehicle sales from 1981 to 2019 were obtained from government data (Natural Resources Canada, 2023a; Statistics Canada, 1999) and fit to an exponential curve that is then used to project future sales for HD vehicles from 2020 to 2050. To validate the projection, values were compared for projected vs historical vehicle numbers per capita assuming a mid-level population growth projection (Government of Alberta, 2023a), as well as personal communication with industry.

The total projected HD vehicle sales for 2020 to 2050 is assumed to be a constant for all scenarios generated by the model, however, the modelled scenarios varied greatly in the vehicle drivetrains and energy carriers used over this period. Options included ICEV using diesel, BEV using grid power, and FCEV using hydrogen. **Sections 3.3 and 3.4** will describe how the sales per year for each vehicle type were calculated.

HD vehicle registrations from 2020 to 2050 were then calculated from the HD vehicle sales, using **Eq. (2)** (also depicted in **Fig. 3.1A**), and solving for the average age of all new HD vehicles sold in a year when 50% of the original fleet size were no longer on the road ($t_{50}$):

$$PR(t) = \frac{M}{1+e^{-b(t-t_{50})}} \tag{2}$$

where **PR(t)** is the percent of HD vehicles at age '**t**' (years) which remain on the road (i.e. are registered), **M** is the total market share (set to 100%), **b** is the decline rate (set to **b** = -0.3), and $\mathbf{t_{50}}$ is the midpoint year when 50% of the HD vehicles have been decommissioned. This survival curve assumes that any movement of vehicle registrations out of the province are matched by used vehicles of a similar age coming into the province in that year.

To implement **Eq. (2)**, a vehicle survival computational model was built where HD truck sales are identified in rows for 1981 to 2050, and columns labelled for the same year range track the number of vehicles of each age class (rows) surviving into the future. The sum of the columns shows the modelled number of registered HD vehicles for each year younger than model year 1981. The computational model is then used to solve for the $t_{50}$ value in **Eq. (2)** that gives the number of registered HD vehicles in Alberta in 2019 (Natural Resources Canada, 2023a). That value for $t_{50}$ is used with **Eq. (2)** and the projected vehicle sales for 2020 to 2050 to project the registered vehicles on the road in Alberta over this period.

The Canadian Vehicle Survey (Statistics Canada, 2010) carried out between 2001 and 2009, indicated that HD trucks are typically used very heavily in the first few years of ownership and then the VKT per vehicle declines with vehicle age as shown in (**Fig. 3.1B**). Compared to the average VKT/vehicle/year for all registered HD trucks, the VKT/yr of new vehicles tend to be 185% higher, while older vehicles (+20 yrs) have VKT/vehicle/yr of only about 15-20% of the average.

These insights helped define **Eq. (3)**, used to calculate total VKT/yr of HD trucking in Alberta with the help of the age structure of registered vehicles calculated previously.

$$\boldsymbol{PV(t) = \frac{M_{Max} - M_{Min}}{1 + e^{-b(t - t_{50})}} + M_{Min}} \quad \textbf{(3)}$$

where **PV(t)** is the percent of fleet average VKT/veh/yr that HD vehicles deliver at age '**t**' (years). $\mathbf{M_{Max}}$ and $\mathbf{M_{Min}}$ are the supremum and infimum for PV(t) (set at 190% and 15%, respectively), **b** is the decline rate (set to **b** = -0.3), and $\mathbf{t_{50}}$ is the year when the VKT/veh/yr is halfway between $M_{Max}$ and $M_{Min}$ (i.e. 102.5%) (See **Fig. 3.1B**)

The value for $t_{50}$ in **Eq. (3)** is determined by expanding the vehicle survival computational model described previously to include calculations on the VKT/yr for each model year and age of trucks over the period from 1981 to 2019. The sum of the columns provided the modelled total of VKT/yr travelled by vehicles sold in Alberta after 1981. The computational model was solved for a $t_{50}$ value that generated total VKT/yr values for HD trucks in Alberta in 2019 that agreed with the government CEUD data (Natural Resources Canada, 2023a). That $t_{50}$ value was then used with **Eq. (3)** to project VKT/yr for the 2020 to 2050 period.

Government data also includes average diesel fuel use by Alberta's registered HD vehicles per km travelled, and the total fuel use by the fleet in the province in 2019 (117 $PJ_{hhv}$ diesel/yr). These data were used to calculate for 2019, fuel consumption of 11.1 average $MJ_{hhv}$ diesel per km (**Table 3.1, Row 1**). Assuming a 35% drivetrain efficiency for ICEV and 41% drivetrain efficiency for FCEV (Alonso-Villar et al., 2022; Forrest et al., 2020; Gray et al., 2022), the fuel hydrogen demand was estimated to be 9.40 $MJ_{hhv}$ per km (**Table 3.1, Row 2**). Similarly, assuming BEVs have a drivetrain efficiency of 78% (Alonso-Villar et al., 2022; Forrest et al., 2020; Gray et al., 2022; Mareev et al., 2017; Peters et al., 2021), the grid power demand was estimated to be 4.98 $MJ_{hhv}$ per km (**Table 3.1, Row 3**). Using these values, it is possible to project the demand for each energy carrier in PJ/yr from the total VKT/yr associated with each vehicle type each year from 2020 to 2050.

**Table 3.1.** Conversion Factors Used to Estimate Energy Carrier Demand by Zero-Emission Vehicles Providing the Same Service as the Incumbent Diesel-Internal Combustion Engine Vehicles

| | Energy Carrier - Vehicle Technology | $MJ_{hhv}$/km | L/km | g $H_2$/km | kWh e/km |
|---|---|---|---|---|---|
| **1** | Diesel-Internal Combustion Engine (ICEV) | 11.1 | 0.287 | - | - |
| **2** | Hydrogen-Fuel cell electric vehicle (FCEV) | 9.40 | - | 66.4 | - |
| **3** | Grid power-Battery electric vehicle (BEV) | 4.98 | - | - | 1.38 |

Footnotes (by row number):

1. From (Natural Resources Canada, 2023a); 38.6 $MJ_{hhv}$/L diesel (The Engineering ToolBox, 2003).
2. Assumes drive train efficiencies of 35% for ICEV and thus 41% for FCEV (0.35/0.41 = 0.85 J $H_2$/J diesel) (Alonso-Villar et al., 2022; Forrest et al., 2020; Gray et al., 2022);
3. Assumes drive train efficiencies of 35% for ICEV and thus 78% for BEV (0.35/0.78 = 0.45 J e/J diesel) (Alonso-Villar et al., 2022; Forrest et al., 2020; Gray et al., 2022; Mareev et al., 2017; Peters et al., 2021); 3.6 MJ/kWh e

While emission factors (g $CO_2/MJ_{hhv}$) for life cycle GHG emissions associated with diesel production are obtained from the literature (**Table 3.2, Rows 1 to 3**), emission factors for hydrogen and grid electricity assumed that existing or promised government policies (Environment and Climate Change Canada, 2023, 2022b; Government of Alberta, 2023b; Romano et al., 2022) will be implemented to ensure the production of very low or zero emissions energy carriers by 2035.

**Table 3.2.** Life Cycle Emission Factors Associated with Diesel, Hydrogen and Electricity Production and Use in Alberta.
*For diesel production from oil sands, estimated values from 2019 are projected into the future. For hydrogen and electricity, projected values assume implementation of existing or promised government policies to transition to low or zero emission energy carrier production by 2035. Values for the period 2036 to 2050 are assumed to be the same as those for 2035.*

| # | Parameter | Units | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Diesel** | | | | | | | | | | | | | | | | | | |
| **1** | Combustion in Vehicle ($CO_2$) | g $CO_2e/MJ_{hhv}$ diesel | 69.5 | | | | | | | | | | | | | | | |
| **2** | Comb. in Vehicle ($CH_4$ & $N_2O$) | g $CO_2e/MJ_{hhv}$ diesel | 0.21 | | | | | | | | | | | | | | | |
| **3** | Oil Recovery, Refining, Transport | g $CO_2e/MJ_{hhv}$ diesel | 29.1 | | | | | | | | | | | | | | | |
| **4** | **Total** | g $CO_2e/MJ_{hhv}$ diesel | **98.8** | | | | | | | | | | | | | | | |
| **Hydrogen** | | | | | | | | | | | | | | | | | | |
| **5** | Blue Hydrogen Production (ATR) | % of total $H_2$ Prod. | 0 | 0 | 0 | 0 | 0 | 20 | 40 | 60 | 70 | 80 | 90 | 95 | 100 | 100 | 100 | 100 |
| **6** | | g $CO_2e/MJ_{hhv}$ $H_2$ | 68.3 | 68.3 | 68.3 | 68.3 | 68.3 | 55.5 | 42.8 | 30.1 | 23.7 | 17.3 | 11.0 | 7.78 | 4.60 | 4.60 | 4.60 | 4.60 |
| **7** | $CO_2$ from upstream | g $CO_2e/MJ_{hhv}$ $H_2$ | 3.70 | 3.70 | 3.70 | 3.70 | 3.33 | 2.96 | 2.59 | 2.22 | 1.85 | 1.48 | 1.11 | 0.74 | 0.37 | 0.37 | 0.37 | 0.37 |
| **8** | $CH_4$ from upstream | g $CO_2e/MJ_{hhv}$ $H_2$ | 13.9 | 13.9 | 13.9 | 13.9 | 13.9 | 12.2 | 10.4 | 8.71 | 6.96 | 5.22 | 3.48 | 3.13 | 2.79 | 2.79 | 2.79 | 2.79 |
| **9** | **Total** | g $CO_2e/MJ_{hhv}$ $H_2$ | **85.9** | **85.9** | **85.9** | **85.9** | **85.5** | **70.7** | **55.8** | **41.0** | **32.5** | **24.0** | **15.6** | **11.7** | **7.76** | **7.76** | **7.76** | **7.76** |
| **Electricity** | | | | | | | | | | | | | | | | | | |
| **10** | Electricity Generation | g $CO_2e/kWh$ | 620 | 540 | 545 | 550 | 523 | 491 | 459 | 427 | 395 | 363 | 311 | 255 | 198 | 142 | 86.2 | 30.0 |
| **11** | | g $CO_2e/MJ_{hhv}$ | 172 | 150 | 151 | 153 | 145 | 136 | 127 | 119 | 110 | 101 | 86.3 | 70.7 | 55.1 | 39.5 | 23.9 | 8.33 |
| **12** | Upstream emissions from NG | % of comb. Emission | 26 | 26 | 26 | 26 | 26 | 24 | 22 | 20 | 18 | 16 | 14 | 13 | 11 | 8.8 | 6.9 | 5.0 |
| **13** | | g $CO_2e/MJ_{hhv}$ electricity | 44.5 | 38.7 | 39.1 | 39.5 | 37.5 | 32.6 | 28.1 | 23.9 | 20.0 | 16.5 | 12.5 | 8.89 | 5.89 | 3.47 | 1.65 | 0.42 |
| **14** | **Total** | g $CO_2e/MJ_{hhv}$ electricity | **217** | **189** | **190** | **192** | **183** | **169** | **156** | **143** | **130** | **117** | **98.8** | **79.6** | **61.0** | **43.0** | **25.6** | **8.75** |

Footnotes (by row number):

1. & 2. Calculated from government data (Government of Alberta, 2023b) for diesel combustion emissions in kg $CO_2e$/L, and a diesel energy content of 38.6 $MJ_{hhv}$/L (The Engineering ToolBox, 2003).
3. Assumes diesel fuel is made from crude oil from oil sands operations in Alberta where upstream emissions are 42% of combustion emissions (42% of Item 1 + Item 2), so 42% * (Item 1 + Item 2) (Nimana et al., 2015).
4. Sum of Items 1 to 3.
5. Assumed source of $H_2$ for HD transport. 0% means that the hydrogen will be generated without carbon capture and storage (i.e. gray hydrogen at 9.67 g $CO_2$/kg $H_2$ or 68.3 g $CO_2$/$MJ_{hhv}$ $H_2$. 100% means that all the hydrogen will be produced by autothermal reforming with the $CO_2$ captured and permanently sequestered (Air Products and Chemicals, Inc., 2023). Some hydrogen may be produced from renewables in the future, with a potential to decrease the life cycle greenhouse gas emissions from what is projected here.
6. Calculated as 68.3 g $CO_2$/$MJ_{hhv}$ * Item 5. The first blue hydrogen production facility using autothermal reforming (93% $CO_2$ captured and storage, (Romano et al., 2022) is expected to come online in late 2024. (https://www.airproducts.com/campaigns/alberta-net-zero-hydrogen-complex), and other facilities have been announced (e.g. https://www.atco.com/en-au/about-us/news/2021/122920-suncor-and-atco-partner-on-a-potential-world-scale-clean-hydroge.html).
7. Assumes 3.7 kg $CO_2$/kg $H_2$ (Romano et al., 2022), but reducing as carbon taxes and other regulations incentivize 90% CCS.
8. Fugitive methane emissions assumed to be 2% (v/v) of all methane recovered in 2020, equivalent to 13.9 g $CO_2e$/$MJ_{hhv}$ $H_2$. Provincial and federal governments have committed to a 75% reduction in these emissions by 2030 (https://www.canada.ca/en/environment-climate-change/news/2022/03/government-of-canada-launches-next-steps-towards-deeper-methane-reductions-from-oil-and-gas.html).
9. Sum of Items 6 to 8.
10. By the late 2020s, virtually all grid electricity emissions in Alberta will be natural gas fired, as coal plants are being phased out. Year 2021 value for Alberta public grid taken from Part 3 (Table A13-10) of ECCC (Environment and Climate Change Canada, 2023). Values for 2022 onward assume a trajectory to achieve 30 g $CO_2e$/kWh emissions electrical grid by 2035 in alignment with stated Canadian government policy (Environment and Climate Change Canada, 2022b; Government of Alberta, 2023b). From 2035 to 2050, assume 30 g $CO_2e$/kWh.
11. Item 10 * 3.6 kWh/MJ.
12. Assumes decarbonization of natural gas recovery in Alberta as described for hydrogen production, so (Item 7 + Item 8)/67.9 g $CO_2$/MJ.
13. Item 11 * Item 13.
14. Item 11 + Item 13.

In the case of hydrogen, Alberta's low-cost natural gas and ample geological storage space for $CO_2$ should make autothermal reforming-CCS of natural gas for the production of 'blue' hydrogen (Air Products and Chemicals, Inc., 2023; Lof and Layzell, 2019; Romano et al., 2022), the dominant technology for new 'fuel $H_2$' production by 2030 (**Table 3.2, Row 5 and 6**). When coupled with regulations and economic incentives mentioned in the previous paragraphs, major reductions are projected in $CO_2$ and $CH_4$ emissions associated with the recovery of the natural gas by 2032 (**Table 3.2, Rows 7 and 8**).

In the case of electricity generation, we assumed that federal and provincial regulations (Environment and Climate Change Canada, 2022a, 2022b; Government of Alberta, 2023b) requiring 30 g $CO_2$e/kWh by 2035 will be implemented.

### 3.3.3 Defining the Business-as-Usual (BAU) Scenario.

The scenario models are first calibrated by creating a reference model to project a "business as usual" (BAU) scenario that assumes no transition, serving as a baseline for comparing various ZEV transition scenarios. In 2019, there were 111,415 registered HD trucks on the road in Alberta driving an average of 95,644 VKT per vehicle per year, resulting in a total of over 10.66 billion VKT/yr (Natural Resources Canada, 2023a) (**Table 3.3, Rows 1 to 3**). Diesel fuel is the energy carrier that is currently used by virtually all HD trucks in Alberta, so the BAU scenario assumes diesel-fuelled internal combustion engines will continue to account for 100% of the market share for new HD trucks in Alberta from 2020 to 2050. As described previously, the sales, number of registered vehicles and total VKT/yr in Alberta will continue to rise over this period.

### 3.3.4 Defining the Transition to Zero-Emission HD vehicles.

The diffusion of new technologies is best defined by 'S' curves (Woo and Magee, 2022; Cox and Alm, 2016; Hipkins and Cowie, 2016; Boretos, 2007; Marchetti, 1991), so **Eq. (1)** for S curves is used to quantify the proportion of new zero emission vehicle HD truck sales over time (**Fig. 3.2**).

Two scenarios are envisaged: one that meets both of Canada's 2030 and 2040 targets in **Fig. 3.2 - Scenario 1** and **Table 3.3 - Rows 5 to 8**, and one that meets only the 2040 target in **Fig. 3.2 - Scenario 2** and **Table 3.3 - Rows 5 to 8** (Transport Canada, 2022a).

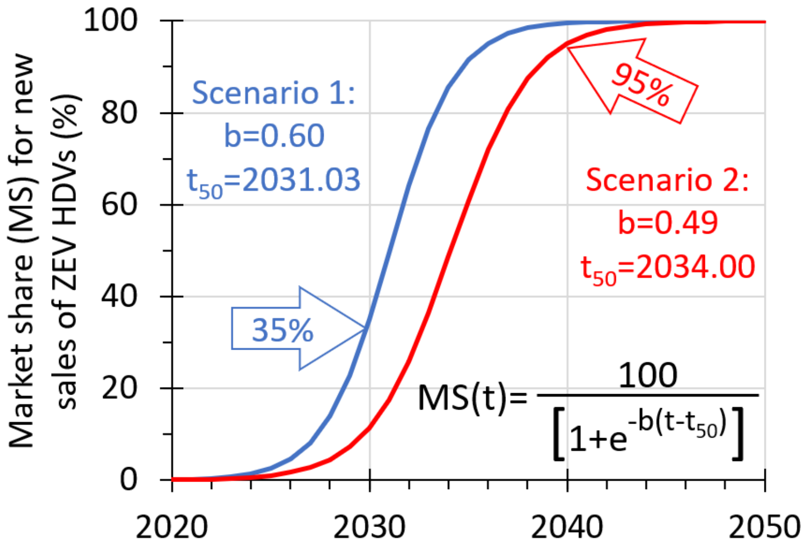



**Fig. 3.2.** Required Market Share (MS) Over Time (t) for Zero-Emission HD Truck Sales. *Sales needed to meet both of Canada's 2030 and 2040 targets (blue line, Scenario 1) or to meet only the 2040 target (red line, Scenario 2). Target values are shown in the arrows. The growth rate values (b) were chosen to be on the lower end, yet still meet the target while ensuring MS values in 2023 were less than 1%.*

**Table 3.3.** Definition of the Scenarios Used in This Study.

| | Parameter | Units | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Government Data for Alberta in 2019 | | | | | | | | |
| **1** | HD Veh. Sales (2019) | Veh/yr | | | | | 6,204 | | | | |
| **2** | Registered HD Veh. (2019) | Vehicles | | | | | 111,415 | | | | |
| **3** | Average VKT (2019) | VKT/veh/yr | | | | | 95,644 | | | | |
| **4** | Total VKT (2019) | B. VKT/yr | | | | | 10.66 | | | | |
| | **Parameter** | **Units** | **BAU Scenario** | **Net-Zero Scenario 1 — Meets 2030 & 2040 Targets** | | | | **Net-Zero Scenario 2 — Meets 2040 Targets** | | | |
| **5** | ZEV Sales by 2030 | % MS | 0% | 35% | | | | Calculated, no target | | | |
| **6** | ZEV Sales by 2040 | % MS | 0% | Calculated, but >95% | | | | 95% | | | |
| **7** | Rate of Adoption (b) **Eq. (3)** | - | - | 0.6000 | | | | 0.4907 | | | |
| **8** | 50% MS ($^{MS}t_{50}$) year **Eq. (3)** | Year | - | 2031.03 | | | | 2034 | | | |
| | **Parameter** | **Units** | **BAU Scenario** | **NZ Scenario 1A — Low BEV share** | | **NZ Scenario 1B — High BEV Share** | | **NZ Scenario 2A — Low BEV share** | | **NZ Scenario 2B — High BEV Share** | |
| **9** | Vehicle Type | | ICEV | BEV | FCEV | BEV | FCEV | BEV | FCEV | BEV | FCEV |
| **10** | Target of Scenario | % MS | 100% | 20% | 80% | 35% | 65% | 20% | 80% | 35% | 65% |
| **11** | Average VKT (2019) | VKT/veh/yr | 95,644 | 30,000 | 112,048 | 50,000 | 120,213 | 30,000 | 112,048 | 50,000 | 120,213 |

Footnotes (by row number):

1. Exponential curve fit for HD vehicle sales in 2019, calculated using historical data for Alberta from 1981 to 2019 (Natural Resources Canada, 2023a; Statistics Canada, 2010).
2. From (Natural Resources Canada, 2023a).
3. From (Natural Resources Canada, 2023a).
4. Calculated as Row 2 * Row 3.
5. ZEV Market Share for HD vehicles in 2030. Canadian Target for Scenario 1 (Transport Canada, 2022b); Calculated for Scenario 2 as 12.3%.

6. ZEV Market Share for HD Vehicles in 2040. Canadian Targets for both Scenario 1 and 2 (Transport Canada, 2022b)
7. Lowest value for growth rate used in S Curve fit **Eq. (3)** that met ZEV targets (Item 5 & 6) yet kept 2023 market share value to less than 1%. Lower values for 'b' would flatten the 'S' curves and project unreasonably high market share percentage in the early 2020s. Higher values for 'b' demand unreasonable adoption rates for new technologies.
8. Calculated from **Eq. (3)** as the date when 50% of market share are ZEV to achieve the targets defined in Rows 5 and 6. See **Fig. 3.2**.
9. BEV, battery electric vehicle using grid power; FCEV, fuel cell electric vehicle using hydrogen; ICEV, internal combustion engine using diesel.
10. Ultimate market share (MS) allocated to the vehicle type defined in Row 9, but the rate of the achieving that market share is defined by the S curve parameters defined in Rows 7 and 8 and shown in **Fig. 3.2**.
11. 11A is the Reference ICEV value from row 3; 11B/11D/11F/11H are set BEV values; 11C/11E/11G/11I are FCEV values calculated from BEV values to meet Row 4. *FCEV example for calculating 11C: 11B*10B*Row 2 + (**11C**)*10C*Row 2 = Row 4*

For the net-zero scenarios, a deeper analysis of the HD truck fleet in Alberta is needed to assess the relative importance of BEV versus FCEV technologies in the transition to net zero. While some HD trucks drive more than the average VKT/veh/yr, some drive significantly less. Also, as discussed previously, vehicles purchased for LH service (200,000+ VKT/veh/yr) may only operate in such a role for the first 4-5 years of their life, after which they are usually sold into SH service. This helps to account for the large observed decline in VKT/veh/year as vehicles age (**Fig. 3.1B**).

There are also HD vehicles such as garbage or cement mixing trucks that are purchased from the beginning to be SH vehicles. In the transition to zero-emission HD trucks, battery electric vehicles should provide a good fit for SH service. SH vehicles typically operate within densely populated area, and return-to-base at the end of the day. They may drive up to 50,000 VKT/Veh/yr, equivalent to an average of 200 km/day, respectively, assuming 5 days per week / 250 days/year. With such service demand, there should be sufficient time to recharge overnight. On the other hand, long haul vehicles need to be able to travel longer distances between refuelling, refuel more quickly, and carry even heavier payloads than what can currently be provided by BEVs. There is a growing consensus that Hydrogen and Fuel Cell Electric is the energy carrier and technology of choice for this sector of the HD truck market (Burke, 2020; Burke et al., 2023; Cunanan et al., 2021; Lajevardi et al., 2022). LH trucks need a fully loaded range of 400+ km before refuelling since many travel up to 1000+ km/day, operate between cities, and only occasionally return-to-base, if they have a base at all.

To determine the proportion of new HD zero-emission truck sales in Alberta that are likely to transition to BEVs versus FCEVs, we assumed that all new vehicles purchased for the SH market would be BEV, while those purchased for the LH markets would be FCEVs. Both vehicle types were assumed to have a higher VKT/veh/yr in the first few years of operation, and then decline with time (**Fig. 3.1B**). We first analyzed the base values for our calibration year of 2019. The average VKT for a HD truck in Alberta in 2019 from **(Table 3.3 – Row 3)** is 95,644 km/veh/year, with the 111,415 registered HD trucks in that year driving a total of 10.66 billion VKT. If it were assumed that all HD trucks in 2019 were long-haul and the split was 100%/0% LH/SH, then that would mean that long-haul trucks would have an average VKT of 95,644 and would only be driving 171,584 km in their first year of operation according to the kilometre module. As it was determined that LH HD trucks can be driving more than 200,000 km in their first year, there must some portion of the population that is short-haul driving a smaller amount of VKT/year, to offset the long-haul VKT.

From bookending a reasonable range (See supplemental materials, **Fig. S1**), a "high BEV" and a "low BEV" scenario were created to capture this range of possibilities. The "low BEV" scenario is calculated through assuming that BEV make up a smaller "20%" of the truck population, and only drive an average 30,000 km/year which equates to 53,820 km in their first year. From this, back calculating the FCEV as per **Table 3.3 - Row 11** gives an average VKT of 112,048 for FCEV, driving 201,012 km in their first year which is a much more reasonable value. The "high BEV" scenario is calculated by assuming the higher end that BEV make up a larger "35%" of the truck population and drive a larger average of 50,000 km/year which equates to 89,699 km in their first year. With a greater percentage of trucks driving less than average, the FCEVs make up for it with an average VKT of 120,213 for FCEV, driving 215,660 km in their first year.

These options for FCEV/BEV market share were assigned to both Scenarios 1 and 2 as defined previously in **Fig. 3.2** and **Table 3.3 - Rows 5 to 8**, to generate four total net-zero scenarios: 1A and 2A, representing the originally defined scenarios with the low BEV transition share and average VKT/year, and Scenarios 1B and 2B with the high BEV transition share and average VKT/year.

## 3.4 Results

### 3.4.1 Projecting sales, registered vehicles and kilometres travelled to 2050

The Alberta Heavy-Duty Truck Model described in **Fig. 3.1** draws on historical data for annual sales (1980 to 2019), registered vehicles (2000-2019) and vehicle kilometres travelled (VKT, 2000 to 2019), to project future trends for all three variables based on a modelled projection of future vehicle sales. As shown in **Fig. 3.3A**, heavy-duty vehicle sales are projected to increase at a rate of 1.4%/yr, a value similar to the projected increase in Alberta's population from 2020 to 2050.

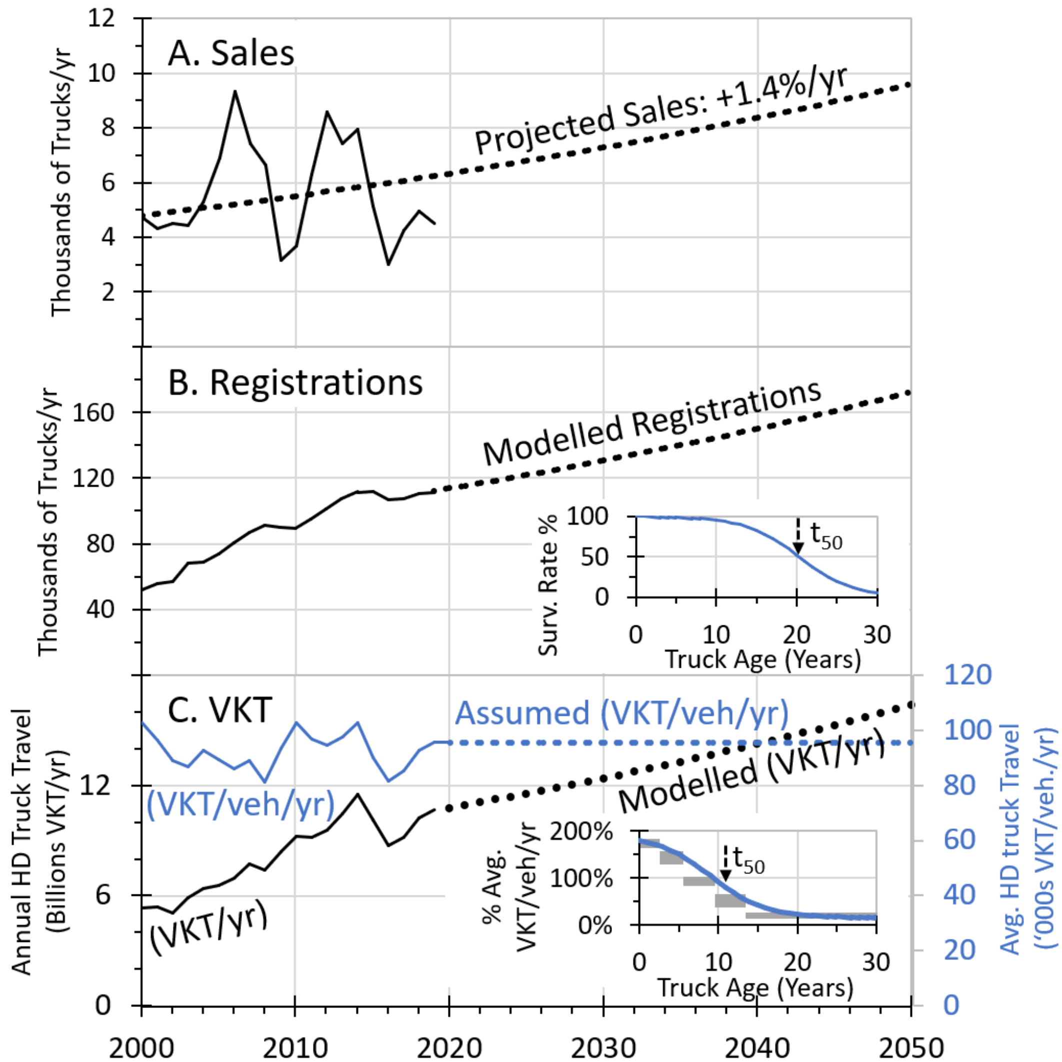



**Fig. 3.3.** The Historical NRCan (Solid Line) and Projected (Dotted Line) Sales (**A**), Registrations (**B**), and Vehicle Kilometres Travelled (VKT) (**C**) for HD Trucks in Alberta.

*A stock and flow model is used to project vehicle registrations for 2019 to 2050 from an exponential growth curve fit of vehicle sales using a survival curve shown in the inset figure of panel B. Similarly, the VKT values were calculated from registered vehicles using the VKT decline curve with vehicle age shown in the inset figure of panel C. Panel C also provides the average historical and projected values for average VKT per registered vehicle per year.*

Using this regression, the rate of vehicle decommissioning was solved using **Eq. (2)** so that the model projections for registered vehicles agreed with the 2019 data, and the projections to 2050 were consistent with historical trends (**Fig. 3.3B**).

Using the projection for heavy-duty vehicle registrations, the changes in VKT/year was solved using **Eq. (3)** so that the model projections for total VKT/year agreed with the 2019 data, and the projections to 2050 were consistent with historical trends (**Fig. 3.3C**).

This core model was then used to assess a business-as-usual scenario and four scenarios for the net-zero transition of Alberta's heavy-duty freight sector to zero emission vehicles.

### 3.4.2 Business-as-Usual (BAU) Scenario Projections

In the BAU scenario, sales of internal combustion engine vehicles continue to rise to 9547 vehicles per year by 2050 (**Table 3.4, Item 1**), driving 16.4 billion km/yr (**Table 3.4, Item 3**) and consuming 4.7 billion L of diesel (**Table 3.4, Item 4**) and generating life cycle emissions of 17.9 Mt $CO_2$e/yr (**Table 3.4, Item 6**).

Compared to 2019 values, the BAU scenario projects a 34% increase in all **Table 3.4** parameters by 2040, and a 54% increase by 2050.

**Table 3.4.** Business-As-Usual Scenario Projections for Sales, Registrations, VKT, Fuel Use, Energy Use, and GHGs of Diesel-HD Vehicles in Alberta to 2050.
*Values for the no-transition scenario are projected for four key years of analysis, 2025, 2030, 2040 and 2050.*

| | Parameter | Units | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| **1** | Diesel Truck Sales | Vehicles (000s) | 6.744 | 7.229 | 8.308 | 9.547 |
| **2** | Diesel Truck Registrations | Vehicles (000s) | 121.1 | 129.8 | 149.2 | 171.5 |
| **3** | Diesel Total VKT | km/Year (Billion) | 11.58 | 12.42 | 14.27 | 16.40 |
| **4** | Diesel Fuel Usage | Litres/Year (Billion) | 3.320 | 3.559 | 4.090 | 4.700 |
| **5** | Diesel Energy Use | $PJ_{hhv}$/Year | 128.1 | 137.4 | 157.9 | 181.4 |
| **6** | Lifecycle GHG Emissions | $CO_2$e/Year (Mt) | 12.66 | 13.57 | 15.59 | 17.92 |

Footnotes (by row number):

1. From (Natural Resources Canada, 2023a).
2. From (Natural Resources Canada, 2023a).
3. Calculated from multiplying 2019 average VKT for HD vehicles (Natural Resources Canada, 2023a) and Row 2.
4. Calculated from Row 3 given 2019 NRCan value of 28.66 L/100km (Natural Resources Canada, 2023a).
5. Calculated from Row 4 using higher heating value (HHV) of 38.6 $MJ_{hhv}$/L diesel (The Engineering ToolBox, 2003).
6. Calculated from carbon intensity of diesel in **Table 3.2**.

### 3.4.3 Net-Zero Scenario Projections for HD Trucking Sales, Registrations, Kilometres Travelled, and Energy Use

Four zero-emission vehicle scenarios were modelled to determine the minimum deployment rate of zero-emission HD trucks needed to achieve the Canadian HD ZEV targets of either 35% by 2030 and near 100% by 2040 (Scenario 1), or just the 2040 target (Scenario 2). The sales projections to 2050 for the four ZEV scenario are provided in **Fig. 3.4**.

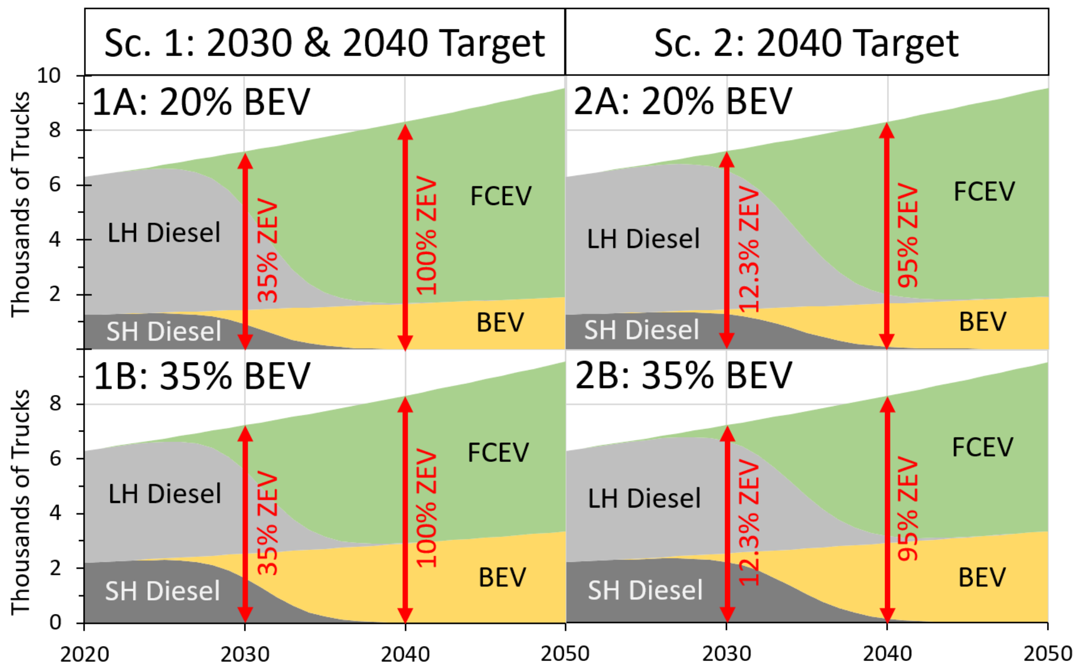



**Fig. 3.4.** Implications of Meeting Canada's 2030 & 2040 Targets for HD Vehicle Sales in Alberta. *Projections shown for Scenario 1 (1A and 1B) and Scenario 2 (2A and 2B), as well for the low BEV scenarios (1A and 2A) and high BEV scenarios (1B and 2B) for vehicle sales. Red values within panels indicate the proportion of ZEV sales to the total sales for that scenario in that year.*

**Table 3.5.** Scenario Projections for Registrations, VKT, and Energy Use of HD Vehicles in Alberta to 2050.
*Columns A and F show the total ZEV values projected for Scenario 1 and 2 respectively, while the remaining columns break down the ZEV growth by ZEV type and high/low BEV scenarios. Column A and F for rows 9-12 displays two values since the sum of ZEVs across low and high scenarios are not the same for Energy Use as they are for the other 3 data sets.*

| | | | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **#** | **Parameter** | **Year** | **Scenario 1 (2030 and 2040 Target)** | | | | | **Scenario 2 (2040 Target Only)** | | | | |
| | | | **ZEV Total** | **1A (Low BEV)** | | **1B (High BEV)** | | **ZEV Total** | **2A (Low BEV)** | | **2B (High BEV)** | |
| | | | (% of Total) | BEV | FCEV | BEV | FCEV | (% of Total) | BEV | FCEV | BEV | FCEV |
| **1** | Registrations (000s of Veh) | 2025 | **0.33 (0.3%)** | 0.07 | 0.26 | 0.12 | 0.21 | **0.16 (0.1%)** | 0.03 | 0.13 | 0.06 | 0.11 |
| **2** | | 2030 | **6.34 (4.9%)** | 1.27 | 5.07 | 2.22 | 4.12 | **2.31 (1.8%)** | 0.46 | 1.85 | 0.81 | 1.5 |
| **3** | | 2040 | **72.6 (49%)** | 14.5 | 58.1 | 25.4 | 47.2 | **51.4 (34%)** | 10.3 | 41.1 | 18 | 33.4 |
| **4** | | 2050 | **148 (87%)** | 29.7 | 119 | 51.9 | 96.4 | **132 (77%)** | 26.4 | 106 | 46.3 | 85.9 |
| **5** | VKT (Billion Km/yr) | 2025 | **0.06 (0.4%)** | 0.01 | 0.05 | 0.01 | 0.05 | **0.03 (0.3%)** | 0 | 0.03 | 0.01 | 0.02 |
| **6** | | 2030 | **1.05 (8.5%)** | 0.07 | 0.98 | 0.19 | 0.86 | **0.38 (3.1%)** | 0.02 | 0.36 | 0.07 | 0.31 |
| **7** | | 2040 | **10.3 (72%)** | 0.65 | 9.68 | 1.89 | 8.44 | **7.72 (54%)** | 0.48 | 7.24 | 1.41 | 6.31 |
| **8** | | 2050 | **15.9 (97%)** | 1.00 | 14.9 | 2.91 | 13 | **15.3 (93%)** | 0.96 | 14.3 | 2.79 | 12.5 |
| **9** | Energy Use (PJ/Year) | 2025 | **0.51/0.48** | 0.02 | 0.49 | 0.05 | 0.43 | **0.25/0.24** | 0.01 | 0.24 | 0.03 | 0.21 |
| **10** | | 2030 | **9.59/9.03** | 0.33 | 9.26 | 0.96 | 8.07 | **3.48/3.28** | 0.12 | 3.36 | 0.35 | 2.93 |
| **11** | | 2040 | **94.3/88.8** | 3.23 | 91 | 9.41 | 79.4 | **70.4/66.3** | 2.41 | 68 | 7.03 | 59.3 |
| **12** | | 2050 | **145/137** | 4.97 | 140 | 14.5 | 122 | **139/131** | 4.76 | 134 | 13.9 | 117 |

Footnotes (by row number):

1. – 4. Modelled registrations taken from stock and flow module results for each scenario.

5. – 8. Modelled vehicle kilometres travelled taken from kilometre module results for each scenario.

9. – 12. Energy use calculated from taking VKT from Rows 5-8 VKT and multiplying first by the assumed Diesel (MJ hhv/ km) from **Table 3.1**, and lastly from **Table 3.1** the corresponding efficiency (0.45 J e./J diesel | 0.85 J $H_2$/J diesel).

Given an incredibly low current deployment of HD ZEVs in Alberta in 2024, the ‘S’ curve growth rate required to achieve the 35% target in 2030 for Scenario 1 results in a projection of virtually 100% ZEV sales by 2040 (**Fig. 3.4, Panel 1A and 1B**). However, these new vehicles must displace the diesel ICE vehicles on the road so ZEV registrations in Scenario 1 account for only 4.9% of all registered heavy-duty vehicles in 2030 (**Table 3.5, A2**), 49% by 2040 (**Table 3.5, A3**) and 87% by 2050 (**Table 3.5, A4**).

In contrast, meeting ‘only’ a 95% ZEV target in 2040 (Scenario 2), required 12.3% of vehicle sales to be ZEV in 2030 (**Fig. 3.4, Panel 2A and 2B**). This more gradual transition results in ZEV registrations in Scenario 2 of 1.8% of all registered heavy-duty vehicles in 2030 (**Table 3.5, F2**), 34% by 2040 (**Table 3.5, F3**) and 77% by 2050 (**Table 3.5, F4**).

However, since newer vehicles are used much more intensively than older vehicles, the ZEV share of total annual vehicle kilometres travelled (VKT/yr) are higher than the share of vehicles on the road. In Scenario 1, projected values for ZEVs as a percent of total VKT/yr are 8.5%, 72% and 97% for 2030, 2040 and 2050, respectively (**Table 3.5, A6 to A8**). In Scenario 2, projected values for ZEVs as a percent of total VKT/yr are 3.1%, 54% and 93% for 2030, 2040 and 2050, respectively (**Table 3.5, F6 to F8**).

### 3.4.4 Net-Zero Scenario Projections for Energy Carrier Demand and Infrastructure Needs

One objective of this study is to assess the impact of a ZEV transition of Alberta’s heavy-duty sector on the demand for conventional diesel and the zero emission energy carriers, electricity, and hydrogen. In the BAU Scenario, diesel demand in Alberta’s HD trucking sector was to increase from 3.3 GL/yr (128 $PJ_{hhv}$/yr) in 2025 to 4.7 GL/yr (181 $PJ_{hhv}$/yr) in 2050 (**Table 3.4, Rows 4 to 5**). However, in the transition to net zero, diesel demand is projected to decrease to 97-92%, 46-28%, and 7-3% of the BAU projection by 2030, 2040, and 2050, respectively (**Fig. 3.5**). The largest projected declines in diesel demand are associated with Scenario 1 in which both 2030 and 2040 targets are met.

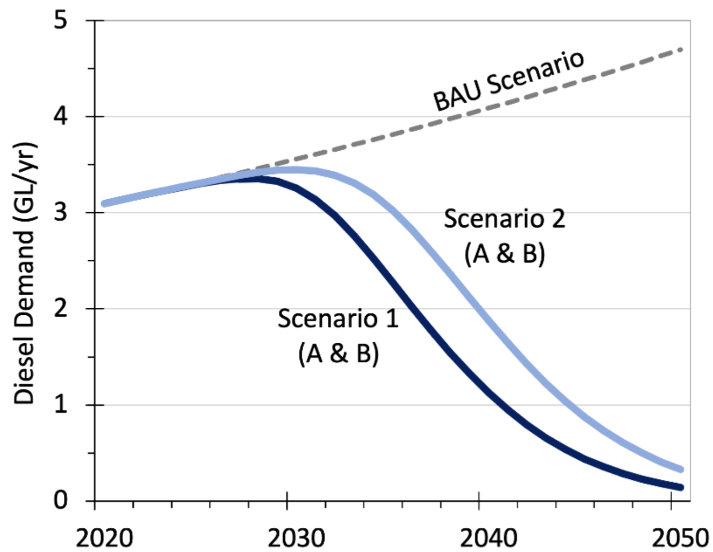



**Fig. 3.5.** Projected Diesel Demand in the Modelled Scenarios.
*The darker blue line shows diesel demand for scenario 1A/1B, which declines sooner than the lighter blue line showing demand for scenario 2A/2B.*

In this study, ZEVs purchased for short haul markets are assumed to be battery electric (BEV, either 20% or 35% of market share) while those purchased for long haul markets are assumed to be hydrogen fuel cell electric (FCEV, either 80% or 65% of market share).

For short haul BEVs in the heavy-duty sector, the energy demand for low/zero GHG electricity is estimated to rise to 1.4 - 4.0 TWh/yr by 2050 (**Fig. 3.6, orange lines**), equivalent to 4.8 - 14.5 $PJ_{hhv}$/year. Assuming this electricity is supplied by 1 MW chargers, each operating at full capacity for the equivalent of 6 hours per day (i.e., 6 MWh/charger/day), a total of 639 - 1826 EV chargers for heavy-duty trucks would be required in Alberta by 2050 (**Table 3.6**).

By comparison, for LH FCEVs, the net zero scenarios projected demand for low/zero GHG hydrogen in 2050 will rise to 2,250 - 2,700 tonnes of hydrogen per day (**Fig. 3.6, green lines**), equivalent to 117 - 140 $PJ_{hhv}$ $H_2$/year (**Table 3.5, Row 12**). Assuming the average $H_2$ fuelling station size and capacity factor increase over the period from 2025 to 2050 (**Table 3.6, Row 7 and 8**), the 6 to 13 stations needed in 2025 would need to grow to 293 to 465 stations by 2050 (**Table 3.6, Row 10 to 13**).

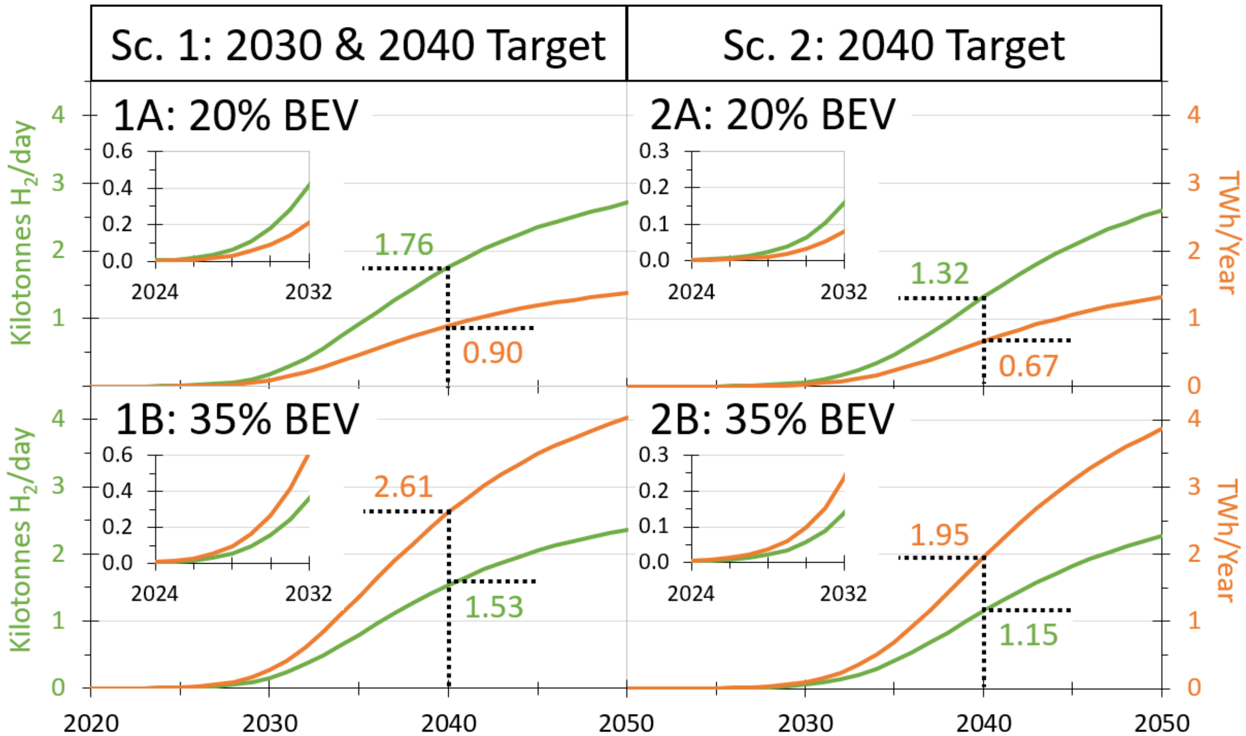



**Fig. 3.6.** Projected Demand for Hydrogen (Green) and Electricity (Orange) in the Four Modelled Net-Zero Scenarios.

*Projections shown for Scenario 1 (1A and 1B) and Scenario 2 (2A and 2B), as well for low BEV as 20% of ZEV sales (1A and 2A) and high BEV as 35% of ZEV sales (1B and 2B) are shown for vehicle sales. Values next to dashed black lines indicate the specific values for fuel usage in the year indicated. Inset figures for each scenario show a zoomed perspective for 2024 to 2032, with a different y-axis scale for data clarity.*

**Table 3.6.** Scenario Projections of Infrastructure Requirements to Meet Future Hydrogen and Electricity Demand.

*Determining necessary fueling and recharging stations based on **Fig. 3.5**'s fuel demand.*

| | Parameter | Units | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| | **A. Charging Requirements for BEVs** | | | | | |
| **1** | Charging Capacity | kW/Charger | 350 | 500 | 750 | 1,000 |
| **2** | Charge per Station | GWh/Year | 0.77 | 1.10 | 1.64 | 2.19 |
| **3** | Scenario 1A | | 3 | 88 | 666 | 921 |
| **4** | Scenario 1B | Total Required | 10 | 257 | 1,942 | 2,688 |
| **5** | Scenario 2A | # of Chargers | 2 | 32 | 473 | 817 |
| **6** | Scenario 2B | | 4 | 93 | 1,379 | 2,384 |
| | **B. Hydrogen Refuelling Requirements for FCEVs** | | | | | |
| **7** | New Station Size | t H2/station/day | 2.0 | 4.0 | 14.0 | 16.0 |
| **8** | Capacity Factor | % | 40% | 55% | 80% | 80% |
| **9** | Delivered H2 | t H2/station/day | 0.8 | 2.2 | 11.2 | 12.8 |
| **10** | Scenario 1A | | 13 | 109 | 388 | 465 |
| **11** | Scenario 1B | Total Required # of | 12 | 95 | 339 | 405 |
| **12** | Scenario 2A | stations | 7 | 41 | 232 | 336 |
| **13** | Scenario 2B | | 6 | 36 | 202 | 293 |

Footnotes (by row number):

1. Assumed average charging capacity of new HD BEV chargers.
2. Charging capacity multiplied by daily charging (6 hours per day), multiplied by days charging per year (365 days of charging per year) (Tanvir et al., 2021), and converted from kWh to GWh.
3. - 6. Dividing the additional electricity demand from each scenario per year by the expected annual new charger capacity and summing the resulting chargers up to each stated year.
7. New FCEV refuelling station size is assumed to increase steadily over time from the assumed minimum financially viable 2 t H2/station/day (Khan et al., 2022) in 2025 to 16 t H2/station/day in 2050.
8. Capacity factor taken from HDRSAM (Argonne National Laboratory, 2017), using their assumption of a maximum 80% capacity factor for nominal station operations.
9. Row 1 * Row 2.
10. - 13. Dividing the additional hydrogen demand from each scenario per year by the expected new station size per year and summing the resulting stations up to each stated year.

### 3.4.5 Net-Zero Scenario Projections of GHG Emissions

When the values from **Table 3.2** for life cycle GHG intensity of diesel, electricity and hydrogen were combined with results from **Fig. 3.5** and **Fig. 3.6**, the life cycle GHG emissions for Alberta's heavy-duty trucking sector can be calculated for each of the net zero scenarios (**Fig. 3.7**).

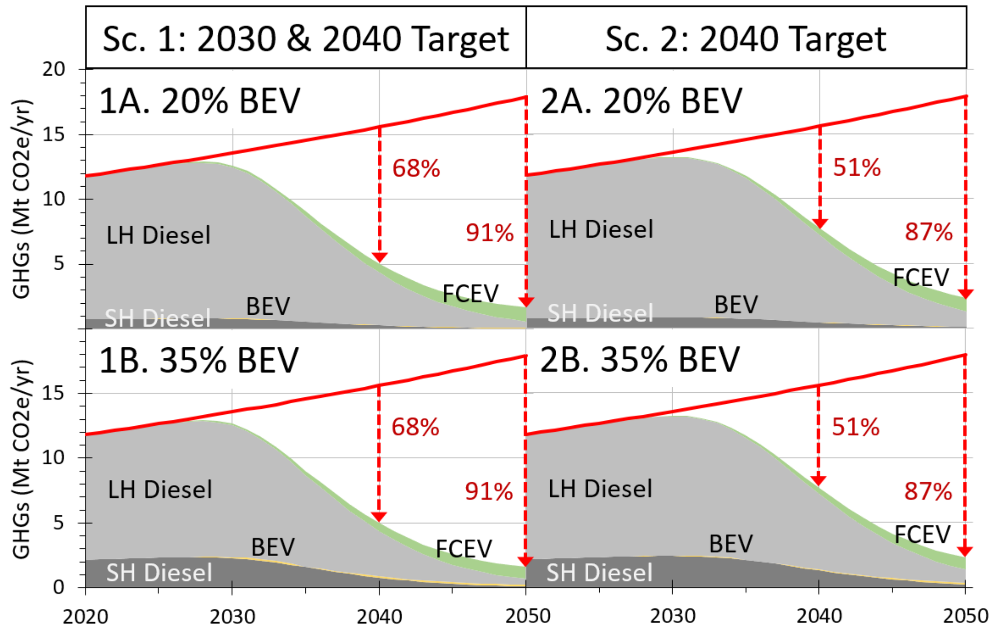



**Fig. 3.7.** Modelled Greenhouse Gas (GHG) Emissions for HD Trucks in Alberta Across All Scenarios Towards 2050.
*Projections shown for Scenario 1 (Sc. 1A and 1B) and Scenario 2 (Sc. 2A and 2B), as well for low BEV as 20% of ZEV sales (1A and 2A) and high BEV as 35% of ZEV sales (1B and 2B) are shown for GHG projections. The declining GHGs for long-haul (LH) diesel (light grey), short haul (SH) diesel (dark grey), battery electric vehicles (BEV) (yellow), and fuel cell electric vehicles (FCEV) (green) are shown in comparison to the diesel business-as-usual scenario modelled by the red line, allowing for comparison of GHG reduction between scenarios.*

Compared to the BAU Scenario, the net zero scenarios project only minor reductions in life cycle GHG emissions by 2030 (2% to 7%), but by 2040 reductions are 51% to 68%, and achieve 87% to 91% (**Fig. 3.7**). While there are emissions associated with electricity and hydrogen production, in a more likely Scenario 2, most (54% - 55%) of the GHG emission are linked to the production and combustion of diesel fuel.

## 3.5 Discussion

### 3.5.1 The Model

The scenario model developed here (**Fig. 3.1**) uses historical and regression-generated data for heavy vehicle sales to generate future projections for registered vehicles (**Fig. 3.3B**), VKT/yr (**Fig. 3.3C**), and diesel fuel demand (**Table 3.4**) that fit well with historical data (2000 to 2019), and population growth projections for Alberta, Canada of 1.4% per year (Government of Alberta, 2023a). Since 2019 is the anchor year for future projections the model did not consider the COVID-19 pandemic, but recent data for 2022 (Environment and Climate Change Canada, 2023) signalled that key indicators of fuel demand and economic activity are returning to pre-pandemic trends.

Since the focus for the scenario projections is 2025 to 2050, the inconsistency between actual and projected energy use during the COVID years is not considered a problem.

Key features of the model inputs and projections include:

- ☐ To fit data on historical sales of new vehicles to registered vehicles for the province, the average half-life of heavy-duty vehicles (i.e. $t_{50}$, **Eq. (2)**) was calculated to be 20 years (**Fig. 3.3B, insert**). Data was not available on imports (or exports) of used, heavy-duty vehicles, but it is hard to envisage that an imbalance of imports would significantly extend the half-life of a vehicle fleet.
- ☐ To project the total VKT/yr for the sector, the model calculated that, at 10 years old, the distance travelled by the average vehicle is reduced to 50% of the distance travelled by young vehicles versus those at end of life. This projection was a good fit to data from a national vehicle survey (Statistics Canada, 2010) (Line vs shaded region of **Fig. 3.3C, insert**).
- ☐ The average distance travelled by the fleet of heavy-duty trucks in Alberta in 2019 is reported to be 95,644 VKT/vehicle/year (**Table 3.3, Item 3**), a value consistent with the previous 19 years (**Fig. 3.3C**). Average fuel efficiency in 2019 was reported to be 0.29 L/km (**Table 3.1, Item 1**), a value that seems low given other studies (Natural Resources Canada, 2000) and consultation with industry (Alberta Motor Transport Association,

personal communication) that places fuel efficiency for this vehicle class between 0.4 to 0.5 L/km.

Discussions with the government organization compiling the dataset on which this work was done (Natural Resources Canada, personal communication) revealed that the fuel efficiency and VKT/veh/yr data are calculated but anchored by more reliable data on registered vehicles numbers and actual fuel consumed by the sector in each year. Therefore, if the L/km data are underestimated, the VKT/veh/yr data are overestimated. In the end, the key purpose for this study is to project future diesel, hydrogen, and electricity demand in a net zero transition, and these values would be the same given values for total vehicle numbers and total fuel consumed.

### 3.5.2 Feasibility of Meeting Government Targets for new heavy-duty vehicle sales

To meet Canada's 2030 target for 35% of heavy-duty vehicle sales (Scenario 1), the model developed here shows that the Alberta trucking sector must bring into service 370-450 new FCEVs and 110-200 new BEVs by 2027, on route to purchasing 1650 to 2020 FCEVs and 510 to 890 BEVs by 2030 **(Fig. 3.4)**.

Providing the electricity for the BEVs requires 0.09 to 0.27 TWh/yr of low-GHG electricity by 2030, equivalent to less than a 0.5% increase in the output of Alberta's public electrical grid in 2019 (Environment and Climate Change Canada, 2023). Assuming this electricity is provided from 500 KW rechargers that are in full use for an average of 6 hours/day, 80 to 250 EV chargers would need to be deployed by 2030.

Providing the hydrogen for the FCEVs requires 155 to 180 t$H_2$/d by 2030, equivalent to about 2-3% of the province's current production of GHG intense $H_2$ as an industrial feedstock (Government of Alberta, 2022; Layzell et al., 2020b). Assuming each hydrogen fuelling stations delivers 4 t $H_2$/day, 39 to 45 fuelling stations would be needed by 2030.

In the global heavy-duty freight vehicle sector, BEVs from manufacturers such as Tesla (Tesla, 2024) and Freightliner (Daimler Truck North America LLC, 2024), and FCEVs from manufacturers such as Hyundai (Hyundai Motor Company, 2024), Nikola (Nikola Corporation, 2024), and Toyota (Kenworth Truck Company, 2024), are currently available in the marketplace; however, few of these vehicles have been deployed in Alberta. Even fewer are built to meet the challenging requirements of the Alberta industry including temperatures that can range from -40°C to +35°C, the need to support A-trains and B-trains with gross vehicle weights of up to 63.5 t, and the requirements for long haul, where new vehicles are being use for up to 200,000 km/year or more (Lof and Layzell, 2019).

While the local industry association has partnered with industry and government to pilot and demonstrate BEVs and FCEVs under real world conditions (Alberta Motor Transport Association, 2022), achieving the federal government's 2030 target for 35% of new vehicle sales remains a substantial challenge, especially for hydrogen supply and fuel cell vehicle deployment that requires an entirely new value chain that does not exist today.

Scenario 2, which targets 95% of new vehicle sales by 2040 is, perhaps, a more credible target for the transition to net-zero energy systems, at least over the period to 2030 when new vehicles must be designed, built and market-tested, and new infrastructure is needed.

Under Scenario 2, the Alberta trucking sector must bring into service 140 to 170 new FCEVs and 40 to 75 new BEVs by 2027, on route to purchasing 580 to 710 FCEVs and 180 to 310 BEVs by 2030 **(Fig. 3.4)**. The electricity needs in 2030 would be less than 0.1 TWh/yr, which could be met by about 90, 500 kW chargers operating 6 hr/day. To support the FCEVs, 55 to 65 $tH_2$/d is needed by 2030, requiring 14 - 17 fuelling stations delivering an average of 4 t $H_2$/day **(Table 3.6)**.

However, Scenario 2 still poses a significant deployment challenge to achieve a 12.3% market share in new vehicle sales with supporting infrastructure by 2030. The next six years (2024-2030) will be crucial for planning and initiating rapid deployment of ZEVs and supporting infrastructure for the 2030 to 2040 period, which is projected to require a near 9-fold increase in annual ZEV sales, resulting in a 22-fold increase in the number of ZEVs on the road and a 20-fold increase in the supply of low-GHG hydrogen and electricity for the sector.

### 3.5.3 The need for infrastructure investments.

To realize the magnitude of growth in the market for zero-emission, heavy-duty vehicles, Scenario 2 requires major infrastructure investments in the 2030s that typically take many years or even a decade to be deployed. For example, by 2040, hydrogen demand of over 1100 $tH_2$/day (**Fig. 3.6, Scenario 2**) for the heavy-duty trucking sector in Alberta, would necessitate major new capacity for the production, storage and pipeline distribution, especially if other sectors (e.g. rail, medium-duty and off-road vehicles, and some industry sectors) are also using hydrogen to achieve their zero-emission targets. Work needs to begin now to design, resource and build the necessary infrastructure for this scale and rate of deployment. Unfortunately, this discussion is nascent in Canada today, especially compared to Europe (European Hydrogen Backbone, 2024).

Per kg costs for production, compression, storage, transport and delivery of low GHG hydrogen are reduced significantly by scale (International Council on Clean Transportation et al., 2023; Khan et al., 2022), as will be the cost of the new FCEVs needed to convert the hydrogen into freight services. Therefore, achieving cost parity in comparison with the incumbent diesel-ICEVs requires infrastructure investments that will be essential in achieving net-zero transition targets.

### 3.5.4 Projected impacts on life cycle GHG emissions.

Achieving net-zero GHG emissions will not only require a shift to zero-emission energy carriers and associated end-use service technologies, but also major changes in how those energy carriers are produced to minimize or eliminate GHG emissions. Provincial and federal governments in Canada have policies and regulations to significantly reduce the carbon intensity associated with electricity generation (Canada Energy Regulator, 2021), methane emissions from natural gas recovery and transportation (Environment and Climate Change Canada, 2022c), and oil recovery and upgrading (Government of Alberta, 2020). These were used to generate the forward projections of GHG intensity for energy carriers shown in **Table 3.2** whereby electricity declines from 217 to 9 g $CO_2e/MJ_e$, and hydrogen declines from 86 to 8 g $CO_2e/MJ_{hhv}$ $H_2$ by 2035.

When these GHG intensities are applied to Scenario 2 (**Fig. 3.7**, **right panels**), GHG emissions in 2040 and 2050 are projected to decline by 51% and 87%, respectively, with most of the remaining emissions being associated with the life cycle emissions of diesel ICE vehicles. To achieve net zero, these residual emissions would need to be addressed through negative emission technologies (Courvoisier et al., 2018).

## 3.6 Conclusions

The federal target that 35% of new, heavy-duty vehicle sales will be zero-emission by 2030 is unlikely to be met given the fact that few of the vehicles currently in the marketplace are fit for Alberta's conditions (loads, ranges, winter temperatures), and the supporting infrastructure for

BEVs and FCEVs are not yet in place. This is especially a challenge for FCEVs since they require an entirely new value chain to supply low GHG, fuel-cell grade hydrogen at strategic locations across the province. Given the heavy loads (up to 63.5 t gross vehicle weights) and long distances (fleet average of ~96 thousand km travelled per truck per year), hydrogen fuel cell vehicles are widely considered to be the most credible zero-emission vehicles for the sector, serving up to 80% of vehicle sales (Burke, 2020; Burke et al., 2023; Cunanan et al., 2021).

More feasible, is the potential to meet the federal target that 95% of new, heavy-duty vehicle sales will be zero-emission by 2040 since that target would provide time to deploy zero emission vehicles capable of meeting the needs of the freight sector in Alberta, and putting the infrastructure in place to produce, store, transport and deliver low GHG hydrogen. Since Alberta is a source of inexpensive natural gas that is currently used to make over 5000 t $H_2$/day as an industrial feedstock (Layzell et al., 2020b), and since the region has the geology to support large scale geological storage (Government of Alberta, 2021b), the province is well positioned to make cost-effective, low GHG hydrogen for use as an energy carrier. Southern Alberta also has an excellent wind and solar resources that could be used to make electrolytic hydrogen but the per kg cost is expected to be higher than that from natural gas with CCS (Khan et al., 2022).

Either way, this new production must be deployed in coordination with other parts of the value chain including transportation, storage, fuelling station delivery and demand from vehicles. To realize the projected rate of growth in the entire value chain over the next 15 years and meet the 2040 target, a major coordination effort is required. Government intervention will be needed to reduce the risk among stakeholders along the entire value chain, including offsetting the additional costs associated with the transition compared with the incumbent diesel-ICEVs. As with any chain, it is only as good as the weakest link.

Techno-economic analyses are needed to quantify the nature and magnitude of the incremental costs associated with the transition to net-zero of the heavy-duty trucking sector in Alberta. This analysis should be compared with the contribution that the trucking sector makes to the economy of the province, and the possible sources of funds that could be used to support the transition.

# 4. Economics of a New Value Chain for Hydrogen to Support Transitioning Heavy-Duty Transport in Alberta

## 4.1 Introduction

Projecting the future of heavy-duty freight in Alberta, as outlined in **Chapter 3**, offers valuable insights for both government and industry by showing the potential benefits and challenges of such a large-scale transition. While it is valuable to understand the scale of this transition through data such as HDV sales, low GHG energy supply, and ZEV fuelling/recharging infrastructure, conducting an economic analysis is crucial for clarifying the financial implications, and long-term feasibility of these initiatives for both government and industry.

The long-established diesel trucking industry, with its significant financial investments in both existing infrastructure and production of new diesel vehicles and fuel, presents considerable challenges for transitioning to a net-zero system. Currently, without financial incentives, the heavy trucking industry has few motivations to transition to zero-emission, as this transition presents a large risk potential for the industry not found with current diesel investment (Khan et al., 2022). However, this does not change Canada's or the world's commitment to decarbonizing the heavy-duty trucking industry.

While the Canadian government's first target of having 35% of new HDV sales be zero-emission by 2030 (Environment and Climate Change Canada, 2022a) was deemed overly ambitious in the previous chapter, their second target of reaching near 100% ZEV sales by 2040 remains a key driver of realistic change in this industry. Understanding the financial implications of achieving these transition goals is crucial for Canada and Alberta's ability to meet its rapid transition targets, providing the background for the financial focus of this chapter.

While the cost implications for BEVs are relevant for SH-HDV applications and will warrant future financial investigation, their limited overall impact on heavy-duty emissions (**Fig. 3.7)**, and their contribution to less than 20% of HDV VKT even in high BEV adoption scenarios (**Table 3.3**), make the analysis of hydrogen costs far more critical for this sector. Additionally, BEVs have already been extensively studied in the context of personal vehicles and LDVs, where their impact is more significant due to the high volume of these vehicles and their suitability for short-distance travel. Moreover, the existing technology and infrastructure for BEVs are much more developed, requiring mostly modifications to current infrastructure rather than the creation of an entirely new value chain (Gray et al., 2022).

Therefore, the cost analysis of hydrogen and FCEVs is critical at this stage to fully understand the potential for transforming the heavy-duty freight sector. As discussed in previous sections, transitioning heavy-duty freight to net-zero will require the creation and support of an entirely new hydrogen value chain, focused on the new long-haul FCEV component which will account for 65-80% of future HDV sales (**Table 3.3**). A thorough examination of the costs of the existing LH diesel value chain alongside the new hydrogen value chain (**Fig. 4.1**) is crucial for ensuring a smooth sector transition and enabling a proper comparison of the overall benefits and challenges associated with this transition. Both value chains encompass the same key components: fuel production and delivery, refuelling stations and tax implications, fuel costs, new ZEV manufacturing, and ultimately, the impact on end users, government, and industry.

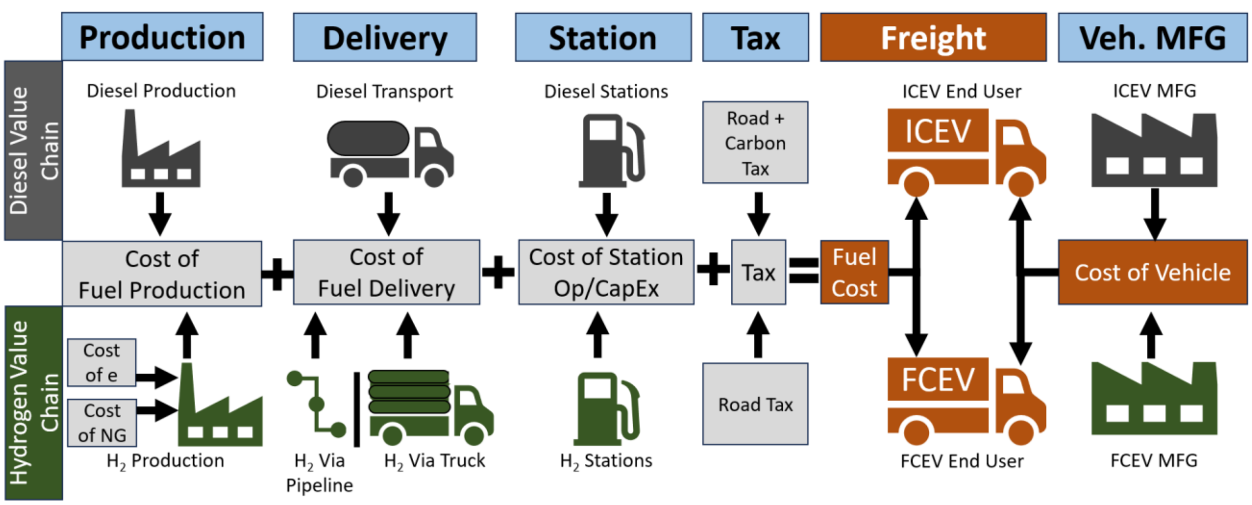



**Fig. 4.1.** Existing Diesel and New Hydrogen Value Chains for Heavy-Duty Long-Haul Freight. *"Cost of e" refers to the cost of electricity, "cost of NG" refers to the cost of natural gas, "C-Tax" is the Canadian carbon tax, "Veh. MFG" denotes vehicle manufacturing, and "Op/CapEx" represents operating and capital expenditure.*

The primary objective of this chapter is to provide an order-of-magnitude estimate for the incremental costs associated with transitioning Alberta's heavy-duty trucking sector to a new value chain that supports fuel-cell electric vehicles. This cost analysis will compare the total cost of ownership between the new hydrogen-based HDV value chain and the existing diesel HDV value chain, considering these costs in the context of the sector's current revenue and operating costs to assess the financial implications. This chapter will also identify potential funding sources to support the incremental costs and facilitate the transition. By offering an initial cost estimate, this study highlights the challenges posed by various variables and unknowns, helping to understand the overall scale and sensitivity of the transition.

Previous studies have addressed specific economic elements of a hydrogen transition, such as the production of low cost and low GHG hydrogen (Jovan and Dolanc, 2020), different methods of transporting hydrogen (Khan et al., 2022), building new hydrogen infrastructure (Argonne National Laboratory, 2017), or determining the cost of new and future FCEVs (Sharpe and Basma, 2022). This chapter explores the larger financial scale, logistical challenges, and feasibility of financing and building an entire new hydrogen value chain to facilitate the transition of heavy-duty transport in Alberta.

## 4.2 Literature Review

To begin the economic analysis, a literature review was conducted to investigate the current diesel and future hydrogen value chains for heavy-duty vehicles in Alberta, providing the necessary background for economic analysis to be performed later in this chapter.

### 4.2.1 The Diesel Value Chain

The diesel value chain in Alberta, as well as globally, is a mature industry with established prices for both end-use fuel and technology. Alberta's significant role in the Canadian diesel market as the largest producer of crude oil and accounting for 80% of the country’s production in 2020 (Canada Energy Regulator, 2023a) further reinforces this maturity. Since the incremental cost of fuel at the pump is already well-documented in Canada and Alberta, calculating the capital and operating costs of the diesel fuel production and transport chains is unnecessary, as further investigation into diesel pricing offers limited benefit.

Although, as shown in **Fig. 4.2** which presents the historical retail price of diesel in Alberta over the past 10 years, diesel prices have become somewhat volatile since the onset of the COVID-19 pandemic.  The red line in **Fig. 4.2** represents the average diesel price from 2022 to mid-2024, illustrating a stark contrast with diesel prices from 2014 to 2021.

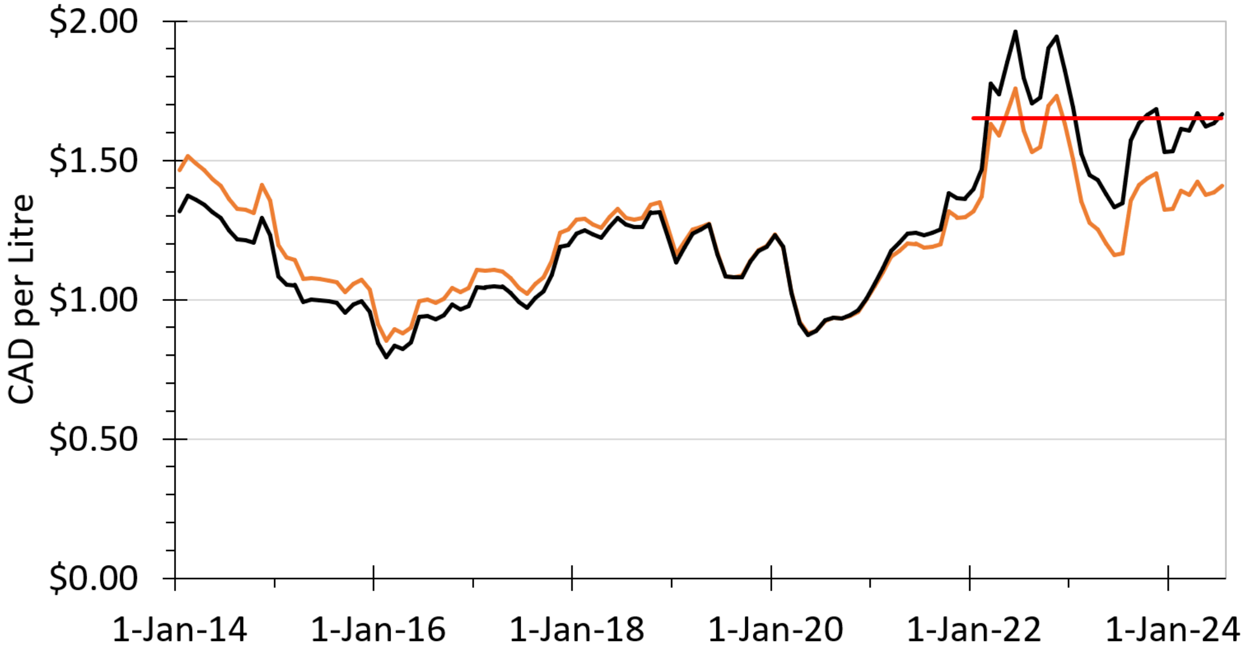



**Fig. 4.2.** Nominal (Black Line) and 2020 Inflation Adjusted (Orange Line) Historical Price of Diesel Fuel in Alberta in the Previous Decade.
*The black line indicates the nominal historical diesel price within Calgary, Alberta specifically (Statistics Canada, 2024b), adjusted for 2020 inflation seen by the orange line (Bank of Canada, 2024) with the red line indicating the $1.65 nominal average of Diesel prices for 2022 to mid-2024.*

Diesel and gasoline stations form a fundamental part of Canada's transportation infrastructure, particularly supporting the country's vast network of trucking and other transportation needs. Diesel fuel is a cornerstone of the Albertan economy, and the extensive network of diesel refuelling stations across Alberta and Canada provides necessary support for these industries. Many people rely on this infrastructure for their livelihoods, either directly through employment at these stations or indirectly through industries that depend on diesel-powered machinery (Scheer et al., 2022). Thus, the transition away from diesel towards more sustainable energy sources must consider these human factors along the value chain to ensure this transition does not result in greater undue harm than the benefits this energy transition will provide.

According to the National Retail Petroleum Site Census published by Kalibrate Canada Inc., as of 2022, there were 11,893 retail gasoline stations operating in Canada, with diesel available at approximately three out of four stations (around 8,900 stations). Of these retail stations, about 82 percent had a convenience store, with a recent increase in revenue diversity with car washes and quick-serve restaurants over time. Compared to Kalibrate Canada's 2004 survey, there are now over 500 more car washes and nearly 900 more quick-serve restaurants at Canadian gasoline stations. This change suggests a shift in gas station trends, where increased competition and franchising have led to a focus on convenience stores and other higher-margin businesses, with refuelling offered as an additional service to attract customers. This diversification may provide benefits for the decline in diesel stations over time but may also create increased barriers to the adoption of hydrogen refuelling, as it provides a level of risk these businesses might not be willing to take on due to a lack of focus on refuelling.

Four main factors come into play when determining the price for a heavy-duty vehicle: range capabilities of the vehicle, Gross Vehicle Weight Rating (GVWR) which refers to the maximum weight a vehicle is designed to carry, the location of vehicle purchase, and for used vehicles, the vehicle's age and condition. While each of these factors can significantly affect the price, this investigation focuses on future/new HDVs, so range, GVWR, and purchase location will be the primary contributors considered.

Historical diesel-ICEV values remain relatively consistent across studies on HDV purchase prices, despite differences in purchase location and range, providing a straightforward basis for comparison and future projection seen in **Fig. 4.3**.

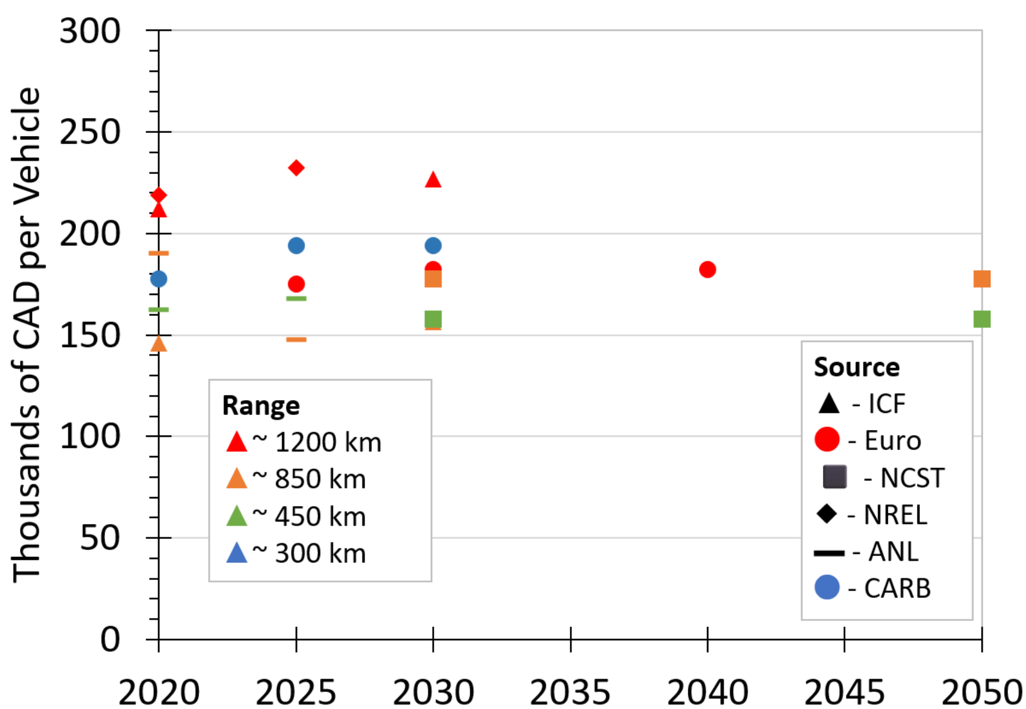


**Fig. 4.3.** Comparison of Diesel-HDV Price Projections in 2020.
*Data taken from a combination of sources including ICF International (ICF International, 2019), in-depth Euro vehicle component analysis from (Gray et al., 2022), National Center for Sustainable Transportation HDV market analysis (Burke, 2020), and an ICCT meta-study for ZEV purchase costs using multiple sources such as NREL, ANL, and CARB. (Sharpe and Basma, 2022).*

Given that this financial investigation focuses on long-haul HDVs, the red and orange points in **Fig. 4.3**, which suggest an expected price range of CAD 175,000 to 250,000, are the most relevant for calculating long-haul HDV costs. In this mature market, diesel vehicles are considered highly dependable compared to newer ZEVs. As a result, it is expected that manufacturers and sellers of diesel ICEVs have little motivation to adjust their pricing until ZEVs approach cost parity. This expected price stability is reflected in **Fig. 4.3**, where the few projections through 2040/2050 show only minor or no price changes.

### 4.2.2 The Hydrogen Value Chain

Compared to diesel, determining the cost of producing hydrogen in Alberta is significantly more complex due to the novel and multiple production methods available, as well as the wide variation in costs and greenhouse gas emissions associated with each method, as highlighted in the literature review.

Producing green hydrogen in Alberta faces significant challenges in achieving economically viable production costs, ideally under CAD 3 per kilogram of hydrogen. The primary determinant of green hydrogen costs produced via water electrolysis is the price of electricity. Electrolyzers, about 76% efficient, require roughly 52 kWh to produce one kilogram of hydrogen. Consequently, each CAD 10/MWh increase in electricity costs adds approximately CAD 0.52 to the hydrogen production cost, excluding CapEx and OpEx (Khan et al., 2022). For instance, raising the electricity price from CAD 20 to CAD 100/MWh can elevate hydrogen costs by 2-3 times, regardless of the electrolyzer CapEx (Khan et al., 2022).

This production also requires nearly-continuous access (ideally 6,000+ hours per year) to low-cost (under CAD 30/MWh), low-carbon electricity. Moreover, with only about 16% of Alberta's electricity generation coming from renewable sources (Environment and Climate Change Canada, 2023), as well as highly variable energy rates, green hydrogen production in the region not only will be more expensive than blue hydrogen, but could unintentionally result in higher emissions as well.

Current blue hydrogen production in Alberta is primarily achieved through steam methane reforming of natural gas, with over 90% of the resulting $CO_2$ emissions captured. The cost of blue hydrogen is sensitive to natural gas prices, which remained relatively stable in North America from 2015 to 2021 (Alberta Energy Regulator, 2023). The analysis from (Khan et al., 2022) indicates that the cost of blue hydrogen if produced at large-scale ($\geq$ 300 tonnes $H_2$/day) centralized production facilities can be less than CAD 1.70/kg $H_2$ when natural gas prices are at or below CAD 4/GJ. However, this hydrogen is unpurified and requires additional processing to meet fuel cell quality standards, adding further costs. With advancements in linking hydrogen production to carbon capture and storage (CCS) technologies at scale, the levelized cost of hydrogen (LCOH) is projected to decrease further to below CAD 1.5/kg $H_2$ with newer blue hydrogen production methods such as ATR, provided natural gas prices remain stable. Even if Alberta natural gas prices rise to CAD 6/GJ, seen only twice in the last 15 years (Alberta Energy Regulator, 2023), the cost of blue hydrogen production would remain at or below CAD 2/kg $H_2$. However, this is dependant on mature large-scale production, which has only recently become a focus of development for Alberta (Air Products, 2021).

Due to the maturity of reforming technologies, blue hydrogen production can remain competitive even in markets that can only support smaller-scale reformers (e.g., 100 tonnes $H_2$/day) and face higher natural gas prices (e.g., CAD 9–15/GJ), with costs ranging from CAD 3.5 to 4.2/kg $H_2$, which remains competitive with green hydrogen production. For this reason, it is assumed that Alberta will continue to rely on blue hydrogen production to 2050, unless green hydrogen becomes more economically viable in the future.

Despite these positive realities with blue hydrogen potential, grey hydrogen remains a major component of Alberta's hydrogen consumption, with approximately 55% of Alberta hydrogen used for heavy oil upgrading, such as bitumen cracking, 38% for the chemical sector and its by-products, and 7% for oil refining (Government of Alberta, 2021a). Although Pathways Alliance, a coalition of Canada's largest oil sands producers, has committed to reducing emissions through initiatives like carbon capture and promoting blue hydrogen, transition progress has been slow. The Alliance's focus on long-term solutions like carbon capture of $CO_2$, delays immediate emission reductions and prioritises maintaining the oil industry's economic interests (The Canadian Press, 2024). As well, there are peer reviewed claims of "selective disclosure and omission, misalignment of claim and action, displacement of responsibility, non-credible claims, specious comparisons, nonstandard accounting, and inadequate reporting" (Aronczyk et al., 2024) that lead to the conclusion that Pathways Alliance is intentionally "greenwashing" their data, evidenced further by their reaction to the anti-greenwashing provision in a federal omnibus bill (Appel, 2024). As a result, grey hydrogen continues to dominate in Alberta, driven by lower costs and established infrastructure, while the shift to cleaner alternatives lags behind.

The three main delivery methods for hydrogen discussed in **Chapter 2** emerge for similar use in Alberta settings. Techno-economic analyses of hydrogen delivery costs suggest that when FCEV market penetration is high (i.e., $H_2$ demand exceeds 50 $t_{H2}$/day) or delivery distances exceed 100 km, the most cost-effective delivery methods are pipelines and liquid hydrogen trucks. However, during the initial phase of lower FCEV market penetration, delivery via tube trailers could serve as a practical interim solution (Khan et al., 2022; Yaïci and Longo, 2022).

In these initial hydrogen stages, compressed hydrogen delivery via tube trailer trucks provides a reasonable solution for gaseous hydrogen delivery within urban transport settings. This method is suitable as studies show truck-delivered hydrogen stations provided the lowest total initial investment cost, including capital costs and normalized investment cost (Khan et al., 2022; Yaïci and Longo, 2022). However, this method is limited by the lower capacity of each tube trailer (around 300-500 kg of $H_2$ per trailer), as well as higher transportation costs per unit of hydrogen leads to inefficiencies in large-scale or long-distance distribution such as pipelines for mature systems, or liquid $H_2$ for long distances.

For higher-capacity storage and long-distance transport to more remote or rural refueling stations in Alberta, liquid hydrogen delivery via trucks offers an effective solution. While the greater energy density and lower transportation costs per unit compared to compressed hydrogen are advantageous, the significant energy consumption and high costs associated with the liquefaction process, along with the expensive infrastructure required to store liquid hydrogen, may make it too costly for remote communities (Khan et al., 2022). Ammonia ($NH_3$) could be a more viable alternative for long-distance distribution, as it stores hydrogen at a high density and can leverage existing infrastructure due to its widespread use in the chemical industry. However, the corrosive properties of ammonia prevent the use of existing fuel storage systems, and along with the additional infrastructure to "crack" ammonia to turn it into usable hydrogen, it makes the rural adoption of hydrogen even more challenging along the value chain.

Delivering compressed hydrogen via pipelines, typically at pressures of 20 to 70 bar, is the most efficient method for transporting large quantities of hydrogen, ranging from 100 to 300 tonnes per day depending on the pipeline's length and diameter. This method is ideal for long-distance transport and large-scale hydrogen distribution networks, but requires much more substantial upfront investments in infrastructure and ongoing maintenance than the previous two methods (Mahajan et al., 2022; Yaïci and Longo, 2022).

Calculating the cost of hydrogen fuelling stations involves a thorough analysis of several key factors. These include the fueling rate and fill time, the types of dispensers and storage options (such as 350/700 bar compressed hydrogen or liquid hydrogen), and the various financial elements such as discount rates, debt ratios, and interest rates. These factors collectively determine the capital needed, as well as the operations and maintenance (O&M), and energy/fuel costs associated with the station. The Heavy-Duty Refueling Station Analysis Model (HDRSAM) provides a resource for investigating these costs in more detail (Argonne National Laboratory, 2017), detailed in **Fig. 4.4** below from their website.

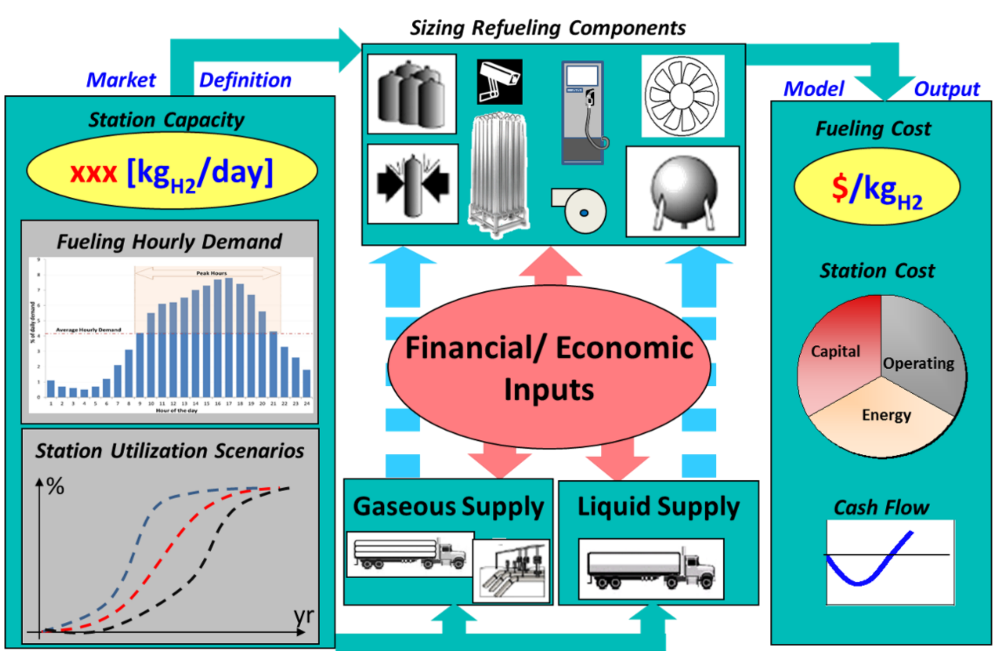



**Fig. 4.4.** Schematic Overview of the HDRSAM Model Used for Station Costs.

*Figure from (Argonne National Laboratory, 2017). The HDRSAM Model integrates financial and economic inputs with hydrogen supply types (gaseous or liquid) to determine refueling component sizes. It defines market needs by station capacity in kilograms per day and hourly fueling demand to assess station utilization. The model outputs fuel costs per kilogram and station costs, including capital expenditure, operating, and energy expenses.*

Establishing hydrogen fuelling stations requires significant capital investment, particularly due to the need for specialized infrastructure and technology to manage hydrogen at high pressures or in liquid form. Additionally, operational costs must be analyzed, considering station usage rates and the variability of fuel prices. Despite these challenges, understanding and optimizing these costs is essential for developing a viable hydrogen infrastructure that can support the widespread adoption of fuel-cell electric vehicles. The HDRSAM model provides detailed costing for multiple station sizes, including capital investment, operational costs, and scalability considerations. This allows for the determination of station pricing for specific scenarios where there is a transformation of station delivery types, which will be used later in **Section 4.3.4.**

The overall future cost of new heavy-duty zero-emission vehicles will be primarily influenced by three key factors: manufacturing advancements, economies of scale, and government incentives. Unlike battery electric vehicles, where the battery pack can account for up to 60% of the vehicle's cost, the largest cost drivers for fuel cell electric vehicles are hydrogen storage (~20%) and the fuel cell propulsion system (~60%) (Sharpe and Basma, 2022), as illustrated in **Fig. 4.5** for an example long-haul FCEV.

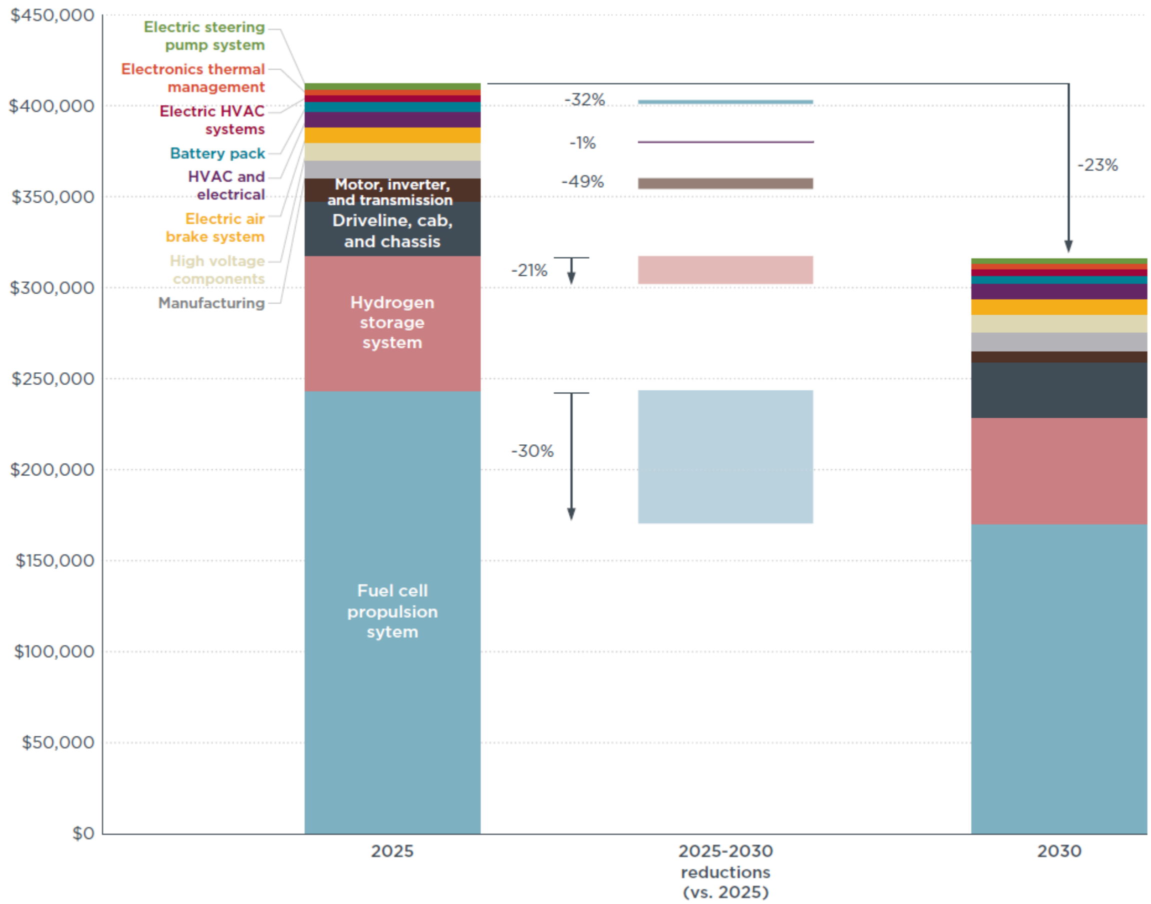



**Fig. 4.5.** Example of Estimated Cost Reductions for Hydrogen Fuel Cell Tractor Truck Components in 2030 and the Estimated Composition of Costs in 2030.
*Figure taken from Figure 6. from (Sharpe and Basma, 2022).*

Manufacturing advancements, such as improvements in battery and fuel cell technologies, directly reduce production costs, making these vehicles more affordable over time. As production scales up, economies of scale further lower costs by spreading fixed expenses across more units and optimizing supply chains. This is evident in **Fig. 4.5**, where significant cost savings are shown to come from the fuel cell and hydrogen storage from this study. Additionally, government incentives play a crucial role in offsetting initial costs for both manufacturers and consumers, encouraging wider adoption of HD ZEVs. These incentives, which can include tax credits, subsidies, and grants, are essential in making HD ZEVs more competitive with traditional diesel vehicles. As mentioned in **Section 3.5.3** however, this discussion is nascent in Canada today, especially compared to Europe (European Hydrogen Backbone, 2024).

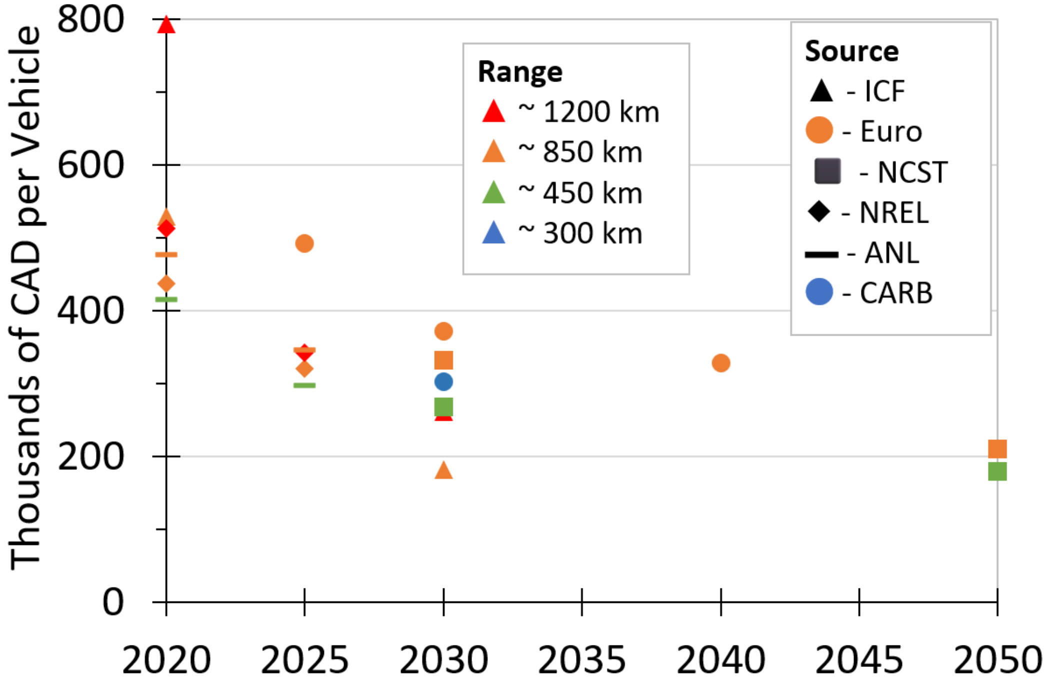



**Fig. 4.6.** Comparison of FCEV Price Projections in 2020.
*Data taken from a combination of sources including ICF International (ICF International, 2019), in-depth Euro vehicle component analysis from (Gray et al., 2022), National Center for Sustainable Transportation HDV market analysis (Burke, 2020), and an ICCT meta-study for ZEV purchase costs using multiple sources such as NREL, ANL, and CARB. (Sharpe and Basma, 2022).*

The projected purchase price of hydrogen trucks through 2050 can be estimated using data from numerous studies, like the approach used for diesel ICEVs. However, since many hydrogen trucks are still in development, these prices remain projections rather than predictive cost models. Studies provide varying estimates on when hydrogen trucks will reach cost parity with diesel trucks, ranging from 2030 to 2040 and beyond, depending on factors such as hydrogen price, HDV range, and GVWR. For example, the (Hydrogen Council, 2020) projects total cost of ownership (TCO) parity as early as 2025, while (Ledna et al., 2022) suggests 2033-2035. (Basma et al., 2022) and (Chauhan et al., 2023) estimate parity between 2028 and 2030, with Basma noting that TCO parity could be reached by 2030 if hydrogen prices fall below CAD 5/kg. The (International Council on Clean Transportation et al., 2023) TCO study suggests that for the heavier FCEVs, they may not see TCO parity until past model year 2040. There is significant uncertainty about the future of FCEV purchasing, with some suggesting that leasing may be preferred to purchasing to mitigate the unknown risk with ZEVs (Liao et al., 2019). Therefore, this study must consider prices and factors specific to Alberta.

### 4.2.3 Costs to HDV End Users

As of 2024, there are two main taxes on fuel and HDVs in Canada. The first of these is the Canadian carbon tax rate, set at CAD 80 per tonne of $CO_2$ equivalent emitted with scheduled annual increases of CAD 15 per tonne on April 1$^{st}$ of each year, reaching CAD 170 per tonne by 2030 (Canada Revenue Agency, 2023). The second of these is the road tax on diesel, which in Alberta includes both federal and provincial components. The federal excise tax on diesel fuel is set at 4.00 cents per litre, and in addition to this, Alberta applies a provincial tax of 13.00 cents per litre (Natural Resources Canada, 2023c). Unlike some other provinces, Alberta does not have additional taxes like a provincial Carbon Tax specifically on diesel fuel; however, the general Carbon Tax does apply to fossil fuels used in the province.

The absence of road taxes for ZEVs has raised concerns about the potential loss of revenue traditionally used for maintaining and developing transportation infrastructure. In response, Canada is exploring options to address this revenue gap as ZEV adoption increases. Proposed solutions include a per-kilometre tax that would charge drivers based on the distance they travel, ensuring all road users contribute to infrastructure upkeep. To temporarily offset the lost tax revenue, Alberta has opted to increase registration fees for ZEVs. Starting in January 2025, EV owners will be required to pay the province CAD 200 annually upon vehicle registration (Global News and Toy, 2024).

The final major cost components for HDV end users include Insurance, Maintenance, Administration, and Labour (IMAL) costs. Each of these factors influences truck purchasers and plays a role in their decision to both purchase new HDVs, and thus to transition from ICEVs to FCEVs. The costs of insurance, maintenance, and labour can be estimated using studies such as the (International Council on Clean Transportation et al., 2023) Total Cost of Ownership (TCO) study, which provides both current and projected costs for FCEVs. Administrative costs a bit more complicated, and are referenced from the CESAR paper (Lof and Layzell, 2019).

The largest portion of these ongoing HDV costs is expected to be labour, primarily due to driver wages. Insurance and maintenance are also key operational costs for HDVs and are somewhat interconnected. While insurance is tailored to the purchaser's specific company and circumstances, maintenance covers routine breakdowns and other unexpected costs from extended use. Insurance may also include coverage for major maintenance costs, such as early engine replacements, though the specifics vary depending on the nature of repairs and policy details. Initially, the complexity and perceived reliability issues of FCEV technology will result in higher insurance premiums (International Council on Clean Transportation et al., 2023). However, FCEV maintenance costs are expected to be lower than those of ICEVs due to fewer moving parts, less wear and tear, and no need for oil changes or exhaust system repairs. As FCEV technology matures and becomes more widely adopted, insurance premiums are expected to decrease, aligning with improved trust and reliability.

Administrative costs are a bit more situational and encompass essential business functions such as marketing, payroll, human resources, accounting, legal services, and board of directors' expenses—core operations required to run a company. While the adoption of FCEVs may introduce changes in areas like regulatory compliance and reporting, the fundamental administrative expenses are likely to remain similar to those currently incurred with ICEVs. These costs are less directly impacted by the type of vehicle in use, as they involve the overall management and operations of the business rather than the day-to-day logistics of fleet management or fuel usage.

### 4.2.4 Determining the Incremental Cost of Ownership for HDVs

To compare the incremental cost of ownership between diesel and hydrogen trucking, the three key financial components of the value chain must be calculated and compared: fuel costs, truck purchase prices, and costs to end users. The most common units for these base components are CAD$/L and CAD$/kg for diesel and hydrogen fuel costs, CAD$/vehicle for purchase prices, and CAD$/km for end-user costs.

As these costs are not directly comparable, a common financial metric is needed to assess the impact of the three key components. The most practical unit for comparison is $/km, which is the same unit used for end-user costs. This can be applied to vehicle purchase prices through PMT (Payment) calculations, which determine the periodic payment needed to finance the vehicle over its lifespan. The PMT function considers the vehicle's purchase price, interest rate, and the total number of periods (the number of years the vehicle is expected to be in service). This calculation, combined with the average kilometres driven per HDV in its lifetime, allows for the conversion of vehicle purchase price into CAD/km. Similarly, fuel costs can also be converted from CAD/litre and CAD/kilogram to the same unit of CAD/km using the efficiency conversion values found in **Table 3.1**.

With fuel costs, truck purchase prices, and end-user expenses all converted to the same financial metric of CAD/km, it becomes possible to compare the incremental cost of ownership between diesel-ICEVs and hydrogen-FCEVs. Additionally, multiplying this value by the kilometres driven in one of the modelled scenarios, translates the incremental cost into the total cost of ownership for the entire HDV sector, a key element of this economic analysis.

## 4.3 Research Methodology

### 4.3.1 Framework for Cost Estimation

**Section 4.3** covers the methodology used in determining the order-of-magnitude estimate for the incremental costs associated with transitioning Alberta's heavy-duty trucking sector to a new hydrogen value chain that supports fuel-cell electric vehicles.

This analysis begins by investigating the key components of both the new hydrogen and existing diesel value chains, including fuel costs (covering production, transport, and fueling stations for hydrogen), as well as the costs associated with new ICEVs, FCEVs, and end users. These analyses, combined with the selection of one of the four scenarios outlined in **Chapter 3** that project the future of HDVs in Alberta, will enable the estimation of the total cost of ownership for new hydrogen HDVs under the selected scenario, as well as for the new hydrogen value chain.

Understanding how the transition impacts costs and identifying areas where strategic investments are needed is vital. To achieve this, the methodology incorporates a range of analyses designed to ensure a robust and reliable evaluation, effectively addressing the inherent complexities of such a large-scale transformation. All prices are calculated in 2020 Canadian dollars (2020 CAD) to ensure consistency across the methodology and allow for the conversion of these costs for other currencies and future years. The economic cost assumptions for this analysis are derived from previous literature reviews and outlined in the following methodology, with the assumptions initially consolidated in **Table 4.1** below.

**Table 4.1.** Economic Cost Assumptions in 2020 CAD for Diesel Internal Combustion Engine Vehicles (ICEV) in the Business-as-Usual (BAU) Scenario (**A**), and Net-Zero (NZ) Scenario (**B**), and for Hydrogen Fuel Cell Electric (FCEV) in the NZ Scenario (**C**).

| | **A. BAU Diesel ICEVs** | **Units** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|---|
| **1** | Canadian carbon tax rate | \$/tonne $CO_2$e | \$95.0 | \$170 | \$170 | \$170 | \$170 | \$170 |
| **2** | BAU annual diesel retail price | \$/L | \$1.65 | \$1.65 | \$1.65 | \$1.65 | \$1.65 | \$1.65 |
| **3** | Annual price per diesel ICEV | 000s \$/Vehicle | | | \$220 | | | |
| **4** | Kilometre cost of insurance | \$/km | \$0.07 | \$0.07 | \$0.07 | \$0.07 | \$0.07 | \$0.07 |
| **5** | Kilometre cost of maintenance | \$/km | \$0.13 | \$0.13 | \$0.13 | \$0.13 | \$0.13 | \$0.13 |
| **6** | Kilometre cost of administration | \$/km | | | \$0.35 | | | |
| **7** | Kilometre cost of labour | \$/km | \$0.50 | \$0.50 | \$0.50 | \$0.50 | \$0.50 | \$0.50 |
| | **B. Net-Zero Diesel ICEVs** | **Units** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| **8** | NZ annual diesel retail price | \$/L | \$1.65 | \$1.65 | \$1.50 | \$1.20 | \$1.20 | \$1.20 |
| **9** | Kilometre cost of insurance | \$/km | \$0.07 | \$0.07 | \$0.07 | \$0.07 | \$0.07 | \$0.07 |
| **10** | Kilometre cost of maintenance | \$/km | \$0.13 | \$0.13 | \$0.13 | \$0.13 | \$0.13 | \$0.13 |
| **11** | Kilometre cost of administration | \$/km | | | \$0.35 | | | |
| **12** | Kilometre cost of labour | \$/km | \$0.50 | \$0.50 | \$0.50 | \$0.50 | \$0.50 | \$0.50 |
| | **C. Net-Zero Hydrogen FCEVs** | **Units** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| **13** | Hydrogen fuel transportation method | | CG+$LH_2$ | CG+$LH_2$ | $LH_2$+Pipe | Pipeline | Pipeline | Pipeline |
| **14** | Cost of low GHG $H_2$ production | \$/kg $H_2$ | \$10.0 | \$6.00 | \$2.50 | \$2.00 | \$1.75 | \$1.75 |
| **15** | Cost of $H_2$ preparation and transport | \$/kg $H_2$ | \$7.00 | \$5.00 | \$4.00 | \$1.50 | \$1.00 | \$0.75 |
| **16** | Capital and operating cost of FCEV station | \$/kg $H_2$ | \$5.00 | \$3.00 | \$2.50 | \$4.00 | \$3.50 | \$3.50 |
| **17** | Annual price per hydrogen FCEV | 000s \$/Vehicle | \$650 | \$500 | \$300 | \$220 | \$220 | \$220 |
| **18** | Kilometre cost of insurance | \$/km | \$0.12 | \$0.08 | \$0.08 | \$0.08 | \$0.08 | \$0.08 |
| **19** | Kilometre cost of maintenance | \$/km | \$0.13 | \$0.10 | \$0.10 | \$0.09 | \$0.09 | \$0.09 |
| **20** | Kilometre cost of administration | \$/km | | | \$0.35 | | | |
| **21** | Kilometre cost of labour | \$/km | \$0.50 | \$0.50 | \$0.50 | \$0.50 | \$0.50 | \$0.50 |

*Footnotes:*

***1.*** *Canadian carbon tax rate (Canada Revenue Agency, 2023).*

***2.*** *The averaged retail price of diesel fuel for ICEVs in the BAU scenario over 2022-2023 year, projected to remain the same for 2025-2050 (Statistics Canada, 2024b).*

***3.*** *Assumed ICEV vehicle price based on various vehicle purchase price studies projected to remain the same from 2025 to 2050 (Burke, 2020; Gray et al., 2022; ICF International, 2019; Sharpe and Basma, 2022).*

***4–7.*** *Assumed price per kilometre from (International Council on Clean Transportation et al., 2023; Lof and Layzell, 2019)).*

***8.*** *The assumed retail price of diesel fuel for ICEVs in the NZ scenario is projected to decline to 2050 with the drop in diesel usage (Statistics Canada, 2024b).*

***9–12****. Assumed price per kilometre from (International Council on Clean Transportation et al., 2023; Lof and Layzell, 2019)).*

***13.*** *Expected transformation of $H_2$ delivery from Alberta study (Khan et al., 2022).*

***14.*** *Assumed cost of H2 production from Alberta study (Khan et al., 2022).*

***15.*** *Cost of H2 transport from Alberta study (Khan et al., 2022).*

***16.*** *Modelled cost of $H_2$ stations from the ANL HDRSAM model (Argonne National Laboratory, 2017).*

***17.*** *Assumed price per FCEV based on various vehicle purchase price studies (Burke, 2020; Gray et al., 2022; ICF International, 2019; Sharpe and Basma, 2022).*

***18–21.*** *Price per kilometre adapted from (International Council on Clean Transportation et al., 2023; Lof and Layzell, 2019)).*

### 4.3.2 Fuel Production Costs

The cost of diesel production and transport within Alberta is well-established, whether it involves the cost of importing diesel from other countries or determining costs based on the local extraction and refining of Alberta oil sands. For determining the price of diesel at the pump for incremental comparison to hydrogen later in this chapter, using the historical average as a basis provides an accurate value for comparison.

In determining the BAU annual diesel retail price (**Table 4.1, Row 2**), an average of diesel prices from 2022 to mid-2024 was determined – also seen in the red line in **Fig. 4.2** - resulting in a value of CAD 1.65 per litre (Statistics Canada, 2024b). This price is used as the basis for the 2025 diesel fuel projection, with the assumption that for the BAU scenario there would be no significant changes in cost or market conditions, allowing this value to remain constant through 2050.

For the NZ annual diesel retail price (**Table 4.1, Row 8**), the same average of CAD 1.65 per litre was applied for the 2025 value (Statistics Canada, 2024b). However, considering the anticipated decline in diesel usage due to the transition to zero-emission vehicles, projections like those from the CER and IEA indicate the alternative vehicles movement will cause a surplus of diesel, and will drive fuel prices down over time (Canada Energy Regulator, 2023b; Healy and Bressers, 2024; IEA, 2022). Consequently, the modelled price is expected from literature to gradually decrease and from CAD 1.65 in 2025/2030 to CAD 1.50 in 2035, reaching CAD 1.20 by 2040, the assumed cost parity date, and remaining stable through 2050.

Determining the cost of producing hydrogen in Alberta, however, is much more complex due to the novel and multiple production methods available, and the wide variation in costs and greenhouse gas emissions associated with each method as seen in the literature review. The province has traditionally relied on grey hydrogen produced through SMR without carbon capture, which results in significant $CO_2$ emissions. However, to align with global and national net-zero targets, Alberta has been shifting towards blue hydrogen production, where SMR or ATR are coupled with CCS technology, allowing for the capture and storage of up to 90% or more of the $CO_2$ emissions.

In projecting hydrogen production costs through 2050, it was assumed that production would initially begin as it currently does within Alberta, with near 80% grey hydrogen (Alberta Energy Regulator, 2024a). While the AER states that by 2032 only 42% of total Alberta hydrogen production will be blue, a majority of remaining grey hydrogen usage at this time is expected from things like heavy oil refining, as discussed in **Section 4.2.2**, whereas the heavy trucking industry is expected to fully transition. Starting with 80% gray hydrogen in 2025, the production is expected to fully transition to blue hydrogen by 2032, aligning with Alberta's capacity for efficient natural gas conversion and carbon capture (Layzell et al., 2020a). Additionally, ATR production with 93% CCS was chosen over SMR due to easier integration of CCS design, and when considering both cost and emissions overall (Oni et al., 2022).

From the examinations of the literature, early production of fuel-cell grade hydrogen is expected to be expensive due to the absence of large-scale 300 t/day $H_2$ reformers, with costs projected at CAD 10.00/kg H2 in 2025. However, these costs are expected to decline rapidly, dropping to CAD 6.00 by 2030 and CAD 1.75 by 2050, as shown in **Table 4.1, Row 14**, driven by economies of scale and reduced production component costs. To ensure a comprehensive analysis, these cost estimates were cross-checked as well against additional reports, such as those from the University of Alberta (Oni et al., 2022), Transition accelerator (Khan et al., 2022), and CESAR (Layzell et al., 2020a), which provided further validation of the proposed transition pathway.

Green hydrogen was chosen to not be represented in this production projection, as explained in **Section 4.2.2**, producing green hydrogen in Alberta faces significant challenges in achieving economically viable production costs (under CAD 3/kg $H_2$), as well as low GHG emissions with only 16% of Alberta's electricity generation coming from renewable sources (Environment and Climate Change Canada, 2023). However, this may change if future green hydrogen production becomes more economically viable, potentially leading to its adoption in the industry.

### 4.3.3 Hydrogen Transport Costs

The cost of hydrogen transport is variable as explained previously, changing depending on station setup, distance from production, and transport method. The chosen transport method significantly impacts the overall cost-effectiveness and feasibility, and The Transition Accelerator report provides detailed data on hydrogen transport systems and costs for Alberta, which is used to establish baseline values for this thesis (Khan et al., 2022).

First, the transport method was determined as shown in **Table 4.1, Row 13**, by assuming steady industry growth outlined in **Section 4.2.2**. This progression begins with early market penetration using compressed gas in tube trailers and liquid hydrogen until 2030, advancing to more developed systems relying on liquid hydrogen and pipelines by 2035, and ultimately reaching a mature system that almost exclusively uses pipeline hydrogen to supply stations by 2040 and beyond.

Next, the cost for each transport method was calculated, adjusted to 2020 CAD, and shown in **Table 4.1, Row 15**. Starting with high preparation and transport costs of an immature system, initial average prices are projected at CAD 7/kg in 2025. These costs will decline slightly to CAD 5/kg with more market maturity by 2030, further decreasing to CAD 4/kg by 2035 with the introduction of pipelines. Finally, a much larger drop to CAD 0.75/kg by 2050 is expected with full maturity of hydrogen pipeline systems, with further cost details seen below in **Fig. 4.7** (Khan et al., 2022).

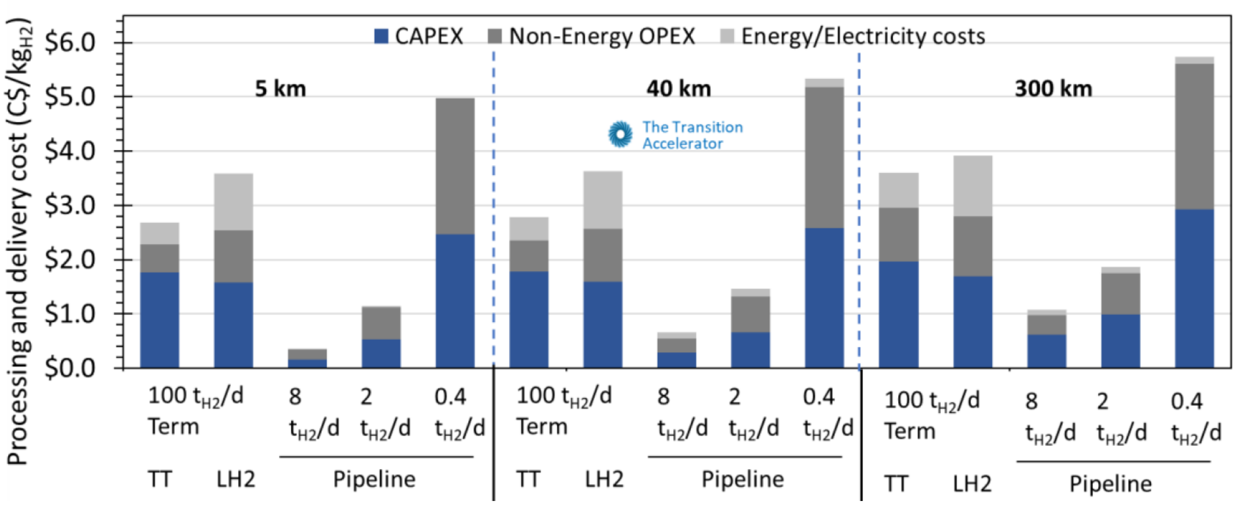



**Fig. 4.7.** Processing and Delivery Costs for Alberta Hydrogen Transport
*Figure adapted from (Khan et al., 2022)*

Overall, it is essential for future considerations to determine how FCEV fuelling stations will accommodate different hydrogen transport methods, as the infrastructure and logistics required to receive and store hydrogen—whether in gaseous or liquid form—will greatly impact the efficiency and cost-effectiveness of the hydrogen value chain. Stations that cannot accommodate the most cost-effective transport methods, such as pipelines, may face higher operational costs—similar to the 2035 transport cost projections (**Table 4.1, Row 15**)—reducing the economic benefits of the hydrogen transition and complicating the process.

### 4.3.4 Hydrogen Fuelling Station Costs

Calculating the cost of hydrogen fuelling stations involves a comprehensive analysis using the Heavy-Duty Refueling Station Analysis Model (HDRSAM) from ANL as the primary resource (Argonne National Laboratory, 2017). The model provides detailed costing for multiple station sizes, including capital investment, operational and maintenance costs, energy costs, and scalability considerations.

Using hydrogen demand projections from Scenario 2A, **Section 3.4.4** estimates the number of new stations required annually to meet demand, and thus which delivery technology is likely for each year. The projected adoption of hydrogen stations starts with smaller liquid hydrogen and compressed gas stations delivered via truck and increases in size over time. By 2035, pipeline stations are introduced and become the standard by 2040. From (Khan et al., 2022), even under large-scale delivery conditions, small hydrogen fuelling stations (0.4 $tH_2$/day) struggle to be economically viable. Therefore, it is assumed that initial refuelling stations will be 2 $tH_2$/day, growing to 16 $tH_2$/day as described in **Section 3.4.4**, and detailed in **Table 3.6**. These station sizes, along with the assumed fuel transportation method from **Table 4.1, Row 13**, were input into the HDRSAM model to determine the $/kg output from the model. Since HDRSAM only provides data up to 10 t/day, projections are made for the 12-16t/day stations based on the rising cost trend from the model projections.

From the results of the HDRSAM modelling, the costs for smaller 2-tonne-per-day compressed gas and liquid hydrogen stations in 2025 are projected to be relatively high, at CAD 5.00 per kilogram of hydrogen produced by the stations. By 2030, with greater market maturity and larger 4-tonne-per-day stations, the cost is projected to drop to CAD 3.00/kg $H_2$. By 2035, new stations are expected to reach 8 tonnes per day, and with liquid hydrogen technology reaching full maturity, costs are expected to fall to a minimum of CAD 2.50/kg $H_2$. However, with the introduction of pipeline stations by 2040 and much larger 14-tonne-per-day stations, costs rise again to CAD 4.00/kg due to higher infrastructure expenses. Market maturity is projected by 2045, with 16-tonne-per-day stations stabilizing costs at around CAD 3.50/kg, a level expected to remain steady through 2050. These HDRSAM cost estimates are detailed in **Table 4.1, Row 16** for use in later modelling.

### 4.3.5 ICEV and FCEV Truck Costs

As detailed in the literature review, the purchase prices of both hydrogen and diesel trucks can be projected up to 2050 using data from the studies described in this chapter's literature review. This financial investigation focuses on long-haul heavy-duty vehicles, making the longer-range red and orange data points in **Fig. 4.3** and **Fig. 4.6** particularly relevant for estimating LH-HDV costs. While historical diesel prices have remained consistent across studies on diesel HDV purchase prices, because many hydrogen vehicles are still in development, the prices in these studies are mostly projections rather than precise cost models.

In this analysis of long-haul HDVs overall, these vehicles are expected to have some of the highest range and GVWR requirements among HDVs, which play a critical role in determining their pricing. For the BAU price of diesel LH-ICEVs, **Fig. 4.3** suggests an expected price range of CAD 175,000 to 230,000 (Burke, 2020; Gray et al., 2022; ICF International, 2019; Sharpe and Basma, 2022). The high-range red points on **Fig. 4.3** represent the most reasonable price range for LH-ICEVs, though they primarily correspond to HDVs on the lower end of GVWR, which indicates the average will be on the higher side of this. Considering these factors, the price of new LH-ICEVs in the BAU was selected to be CAD 220,000, which reflects an average purchase price that considers both range and GVWR requirements for typical long-haul HDVs in Canada (Natural Resources Canada, 2023a). In this mature market, diesel vehicles are considered exceptionally reliable compared to newer ZEVs as talked about previously. Consequently, in the NZ scenario, manufacturers and sellers of diesel ICEVs are unlikely to adjust their pricing until ZEVs approach cost parity. Therefore, the same value of CAD 220,000 will be used for diesel LH-ICEVs in the NZ scenario toward 2050 as well.

The future pricing of hydrogen trucks will be a key factor in determining the adoption rate and the feasibility of transitioning from diesel. Critical elements influencing this include manufacturing advancements, economies of scale, and government incentives. As shown in **Fig.**

**4.6**, it is challenging to predict the vehicle purchase price decline for FCEVs through 2050, as projections for LH-FCEVs beyond 2030 are lacking. Even up to 2030, the estimated prices vary widely, ranging from CAD 250,000 to 800,000 (Burke, 2020; Gray et al., 2022; ICF International, 2019; Sharpe and Basma, 2022).. This discrepancy arises primarily because these studies cover a broad spectrum of vehicles, varying in both range and GVWR, similar to the situation with diesel ICEVs.

To address these issues, the vehicle price decline for FCEVs was determined based on two primary factors: the expected date of cost parity and the initial vehicle purchase price in 2025. Studies from **Fig. 4.6** provide insights into when hydrogen trucks will reach cost parity with diesel, with the ICCT study offering the closest analysis relevant to Alberta (International Council on Clean Transportation et al., 2023). While their "*Figure 14. Total cost of ownership parity sensitivity to diesel and hydrogen fuel prices*" suggests green hydrogen FCEVs will not reach parity until after 2040, Alberta's lower-cost blue hydrogen production is expected to enable cost parity by 2040 through this study.

For the initial FCEV price in 2025, based on higher range and GVWR values from the **Fig. 4.6** sources and personal communication from AMTA and AZETEC, a reasonable estimate for a new long-haul FCEV in Alberta is CAD 650,000. This value, starting in 2025, is shown in **Table 4.1, Row 17**, with a linear decline to CAD 220,000 by the 2040 parity date from ICCT. While a straight-line price decline is used here, the actual decrease will likely follow an S-curve, similar to those discussed in **Chapter 3**. The linear assumption is applied here due to greater uncertainty in these projections, whereas the **Chapter 3** models are much more reliable in their data.

There are other factors further to this that will influence the future price of FCEVs, such as the expected depreciation of these vehicles and how that affects their total cost of ownership. However, since these vehicles are not yet in service, tracking their life cycles is currently not possible, and thus depreciation costs are excluded from this analysis. This factor should be considered in future cost studies.

### 4.3.6 Total Cost of Heavy-Duty Truck Ownership

With the base cost components of this transition now calculated, the next step is to apply them to a reasonable transition projection for Alberta to determine the total costs associated with that scenario, and thus the investment required for the transition as a whole. It was previously determined from **Chapter 3** that "The federal target that 35% of new, heavy-duty vehicle sales will be zero-emission by 2030 is unlikely to be met", and thus either Scenario 2A (80% FCEV sales) or Scenario 2B (65% FCEV sales) lead as the most reasonable scenarios to investigate. As one of the primary goals of this chapter is to provide an order of magnitude estimate for the cost of this transition, investigating the high hydrogen scenario of Scenario 2A makes sense, as it will effectively define the upper limit of this transition cost and highlight the significant scale of the potential expenses. Along with Scenario 2A, providing values from the BAU Scenario as well will help establish a basis for comparing the costs and benefits of Scenario 2A to Alberta's current infrastructure and value chain.

The information from Scenario 2A and the BAU Scenario relevant for calculating the transition costs, including vehicle sales, VKT, fuel demand and efficiency, infrastructure, and GHG emissions, are tabulated in **Table 4.2** below. The data is organized by vehicle type, and for ICEVs by NZ or BAU scenario.

**Table 4.2.** Projected Estimates for Alberta's Long-Haul (LH) Heavy-Duty Freight Sector Including Diesel Internal Combustion Engine Vehicles (ICEV) in the Business-as-Usual (BAU) Scenario (**A**), and Net-Zero (NZ) Scenario (**B**), and for Hydrogen Fuel Cell Electric (FCEV) in the NZ Scenario (**C**).

| | **A. BAU Diesel ICEVs** | **Units** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|---|
| **1** | Annual LH ICEV sales | 000s Vehicles/Year | 5.39 | 5.78 | 6.20 | 6.65 | 7.12 | 7.64 |
| **2** | Total registered LH ICEVs by year | 000s Vehicles | 96.9 | 104 | 111 | 119 | 128 | 137 |
| **3** | Total annual VKT driven by LH ICEVs | Billion VKT/Year | 10.9 | 11.6 | 12.5 | 13.4 | 14.3 | 15.4 |
| **4** | Annual VKT per LH ICEV | VKT/Vehicle/Year | 112,055 | | | | | |
| **5** | Efficiency of diesel use | L/km | 0.287 | | | | | |
| **6** | Annual fuel demand per LH ICEV | L/Vehicle/Year | 32,115 | | | | | |
| **7** | Annual LH diesel fuel demand | GL/Year | 3.11 | 3.34 | 3.58 | 3.83 | 4.11 | 4.40 |
| **8** | Annual LH diesel energy demand | $GJ_{HHV}$ Diesel/Year | 120 | 129 | 138 | 148 | 159 | 170 |
| **9** | Tailpipe GHG emissions per litre of diesel | kg $CO_2$/L | 2.689 | | | | | |
| **10** | Total annual tailpipe GHG emissions | Mt $CO_2$/Year | 8.37 | 8.97 | 9.62 | 10.3 | 11.0 | 11.8 |
| | **B. Net-Zero Diesel ICEVs** | **Units** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| **11** | Annual LH ICEV sales | 000s Vehicles/Year | 5.33 | 5.07 | 2.35 | 0.33 | 0.03 | 0.003 |
| **12** | Total registered LH ICEVs by year | 000s Vehicles | 96.8 | 102 | 97.6 | 78.2 | 54.2 | 31.4 |
| **13** | Total annual VKT driven by LH ICEVs | Billion VKT/Year | 10.8 | 11.3 | 9.89 | 6.14 | 2.86 | 1.07 |
| **14** | Annual VKT per LH ICEV | 000s VKT/Veh./Year | 112 | 111 | 101 | 78.5 | 52.7 | 34.2 |
| **15** | Annual fuel demand per LH ICEV | 000s L/Veh./Year | 32.1 | 31.7 | 29.0 | 22.5 | 15.1 | 9.81 |
| **16** | Annual LH diesel fuel demand | GL/Year | 3.10 | 3.23 | 2.84 | 1.76 | 0.82 | 0.31 |
| **17** | Annual LH diesel energy demand | $GJ_{HHV}$ Diesel/Year | 120 | 125 | 109 | 67.9 | 31.6 | 11.9 |
| **18** | Total annual LH ICEV tailpipe GHG emissions | Mt $CO_2$/Year | 8.35 | 8.69 | 7.62 | 4.73 | 2.20 | 0.83 |
| | **C. Net-Zero Hydrogen FCEVs** | **Units** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| **19** | Annual LH FCEV sales | 000s Vehicles/Year | 0.06 | 0.71 | 3.85 | 6.31 | 7.09 | 7.63 |
| **20** | Total registered LH FCEVs by year | 000s Vehicles | 0.13 | 1.85 | 13.7 | 41.1 | 73.7 | 106 |
| **21** | Total annual VKT driven by LH FCEVs | Billion VKT/Year | 0.03 | 0.36 | 2.58 | 7.24 | 11.5 | 14.3 |
| **22** | Annual VKT per LH FCEV | 000s VKT/Veh./Year | 198 | 193 | 189 | 176 | 156 | 135 |
| **23** | Daily hydrogen fuel demand | 000s t $H_2$/Day | 0.005 | 0.06 | 0.47 | 1.32 | 2.09 | 2.60 |
| **24** | Annual hydrogen energy demand | $PJ_{HHV}$ $H_2$/Year | 0.24 | 3.36 | 24.3 | 68.0 | 108 | 134 |
| **25** | Efficiency of Hydrogen use | g $H_2$/km | 66.4 | | | | | |
| **26** | $H_2$ delivered per new station | Tons $H_2$/Day | 2.00 | 4.00 | 8.00 | 14.0 | 16.0 | 16.0 |
| **27** | Capacity factor of new stations | % Capacity | 40% | 55% | 70% | 80% | 80% | 80% |
| **28** | Annual new fuelling stations | New Stations | 6 | 11 | 23 | 16 | 10 | 7 |
| **29** | Total fuelling stations by year | Total Stations | 6 | 40 | 134 | 231 | 295 | 335 |

*Footnotes (by row number):*

***1–3.*** *From **Chapter 3, Fig. 3.4**. and **Table 3.5**.*

***4.*** *Calculated from (**Row 3**) / (**Row 2**)*

***5.*** *From Alberta CEUD (Natural Resources Canada, 2023a)*

***6.*** *Calculated from (**Row 4**) * (**Row 5**)*

***7.*** *Calculated from (**Row 3**) * (**Row 5**)*

***8.*** *Calculated from (**Row 7**) * (38.6 MJ of diesel per L of diesel (The Engineering ToolBox, 2003))*

***9.*** *From **Chapter 3, Table 3.2.***

***10.*** *Calculated from (**Row 7**) * (**Row 9**)*

***11.–13. From Chapter 3, Fig. 3.4.*** *and **Table 3.5**.*

***14.*** *Calculated from (**Row 13**) / (**Row 12**)*

***15.*** *Calculated from (**Row 14**) * (**Row 5**)*

***16.*** *Calculated from (**Row 13**) * (**Row 5**)*
***17.*** *Calculated from (**Row 16**) * (38.6 MJ of diesel per L of diesel (The Engineering ToolBox, 2003))*
***18.*** *Calculated from (**Row 16**) * (**Row 9**)*
***19–21.*** *From **Chapter 3, Fig. 3.4.** and **Table 3.5**.*
***22.*** *Calculated from (**Row 21**) / (**Row 20**)*
***23.*** *From **Chapter 3, Fig. 3.6.***
***24.*** *Calculated from (**Row 21**) * (9.40 $MJ_{HHV}$ $H_2$/km) (**Table 3.1, Row 2**)*
***25.*** *Calculated from (**Row 23**) * (365 days/year) / (**Row 21**)*
***26.–29***. *From **Chapter 3, Table 3.6.***

There are several direct costs and potential savings which contribute to the total cost of ownership for HDV end users, including Insurance, Maintenance, Administration, and Labour. The switch to hydrogen trucks must demonstrate clear economic benefits over diesel, and each of these factors influences truck purchasers and plays a key role in their decision to transition from ICEVs to FCEVs.

The costs of insurance, maintenance, and labour were estimated using the ICCT TCO study (International Council on Clean Transportation et al., 2023), which provides current and projected costs for ICEVs and FCEVs in various U.S. regions. To apply these values to Alberta, the data for the Washington and Texas regions were averaged, as they most closely reflect Alberta's conditions both geographically and economically. The "current" 2022 average values for insurance, maintenance, and labour were converted from $/mile to $/km and applied to 2025, adjusting the currency to 2020 CAD as well. The same process was followed for the ICCT's 2030 and 2040 projections, with linear trends applied between the 2025 and 2030, and between the 2030 and 2040 values. These results are tabulated in **Table 4.1**, with 2040 values assumed to remain constant through 2050.

Labour, primarily due to driver wages, is expected to remain the largest ongoing cost, estimated at CAD 0.50/km across all scenarios, as wages are not expected to change significantly during the transition. Insurance costs for ICEVs are expected to stay stable at around CAD 0.07/km. Initially, FCEVs will have higher insurance premiums due to the complexity and perceived reliability issues (International Council on Clean Transportation et al., 2023), with costs estimated at CAD 0.12/km in 2025, declining to CAD 0.08/km by 2030, though not expected to fall below ICEV levels. Future FCEV maintenance costs are anticipated to be lower than ICEVs due to benefits such as fewer moving parts and more. Both FCEVs and ICEVs have a maintenance cost of CAD 0.13/km in 2025, with ICEV costs remaining constant through 2050, while FCEV costs are projected to decline to CAD 0.10/km by 2030 and CAD 0.09/km by 2040.

Administrative costs, referenced from the CESAR paper (Lof and Layzell, 2019), include costs such as fleet management, human resources, regulatory compliance, office space, accounting and record-keeping. These costs are expected to remain similar for both FCEVs and ICEVs, with a consistent value of CAD 0.35/km across all scenarios, making them a relatively minor factor in the transition.

To calculate the additional cost applied to diesel fuel due to the increase in federal carbon tax, the $CO_2$ emissions from one litre of diesel must first be determined. Using the tailpipe emission value from **Table 4.2, Row 9** (2.689 kg $CO_2$e/L), the carbon tax can be calculated by multiplying the tax rate (CAD/tonne $CO_2$e) by the amount of $CO_2$ emitted per litre. With the carbon tax set at CAD 95/t $CO_2$e in 2025 and rising to CAD 170/t $CO_2$e in 2030, this results in an added cost of approximately CAD 0.26 per litre in 2025, increasing an additional CAD 0.20 per litre to CAD 0.46 by 2030. This value can then be added to the base diesel price in both scenarios to determine the final retail price of diesel.

As talked about in **Section 4.2.4**, the most practical unit for comparison of HDV values is CAD/km. This can be applied to vehicle purchase prices through PMT (Payment) calculations, which determine the periodic payment needed to finance the vehicle over its lifespan. The PMT function is calculated using the vehicle's purchase price, interest rate, and the total number of periods (the number of years the vehicle is expected to be in service) using the formula:

$$\boldsymbol{PMT = \frac{r * PV}{1-(1-r)^{-n}}} \quad \textbf{(4)}$$

For the example value of CAD 0.24 from **Table 4.3, Row 4**, the PMT was calculated using the formula "=PMT(0.1,20,220000)*20/2144836". In this formula, PMT represents the annual payment required to repay a loan, where 0.1 (r) is the assumed annual interest rate of 10%, 20 (n) is the number of periods in years, and CAD 220,000 is the present value (PV), or the initial loan amount. The result of the PMT function is then multiplied by 20 to determine the total payments over the loan's lifetime and divided by 2,144,836 km/year, which represents the average total VKT for an HDV. This calculation converts the total payment amount into a cost-per-kilometre value, enabling a direct comparison with other costs in the analysis.

Fuel costs can be standardized to CAD/km by converting from CAD/litre and CAD/kilogram using the efficiency conversion values from **Table 3.1**, which are 0.287 L/km for diesel and 66.4 g $H_2$/km for hydrogen. For example, the 2025 BAU diesel cost of CAD 1.65/L is divided by 0.287 L/km, resulting in 0.47 CAD/km, as shown in **Table 4.3, Row 3**. Similarly, the total cost of delivered hydrogen from **Table 4.1, Rows 15, 16, and 17** is added together and displayed in **Table 4.3, Row 9**. Dividing this by 0.0664 kg/km gives the final CAD/km value, which is presented in **Table 4.3, Row 10**. With all values converted to CAD/km and tabulated in **Table 4.3**, the economic analysis for Scenario 2A can now be conducted for Alberta.

**Table 4.3.** Projected Calculated Costs for Fuel and Vehicles in Alberta's Heavy-Duty Freight Sector Including Diesel Internal Combustion Engine Vehicles (ICEV) in the Business-as-Usual (BAU) Scenario (**A**), Net-Zero (NZ) Scenario (**B**), and for Hydrogen Fuel Cell Electric Vehicles (FCEV) in the NZ Scenario (**C**).

| | A. BAU Diesel ICEVs | Units | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| 1 | Carbon tax add-on for diesel retail price | $/L | - | $0.20 | $0.20 | $0.20 | $0.20 | $0.20 |
| 2 | Total BAU cost of diesel fuel | $/L | $1.65 | $1.85 | $1.85 | $1.85 | $1.85 | $1.85 |
| 3 | Kilometre cost of diesel | $/km | $0.47 | $0.53 | $0.53 | $0.53 | $0.53 | $0.53 |
| 4 | Kilometre cost of amortized truck capital expenditure | $/km | $0.24 | | | | | |
| | **B. Net-Zero Diesel ICEVs** | **Units** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| 5 | Carbon tax add-on for diesel retail price | $/L | $0.00 | $0.20 | $0.20 | $0.20 | $0.20 | $0.20 |
| 6 | Total NZ cost of diesel fuel | $/L | $1.65 | $1.85 | $1.70 | $1.40 | $1.40 | $1.40 |
| 7 | Kilometre cost of diesel | $/km | $0.47 | $0.53 | $0.49 | $0.40 | $0.40 | $0.40 |
| 8 | Kilometre cost of amortized truck capital expenditure | $/km | $0.24 | | | | | |
| | **C. Net-Zero Hydrogen FCEVs** | **Units** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| 9 | Total cost of delivered $H_2$ fuel | $/kg $H_2$ | $22.00 | $14.00 | $9.00 | $7.50 | $6.25 | $6.00 |
| 10 | Kilometre cost of hydrogen fuel | $/km | $1.46 | $0.93 | $0.60 | $0.50 | $0.41 | $0.40 |
| 11 | Kilometre cost of amortized truck capital expenditure | $/km | $0.71 | $0.55 | $0.33 | $0.24 | $0.24 | $0.24 |

*Footnotes (by row number):*

1. *Calculated as change in C-Tax price from base (**Table 4.1, Row 1**) * (**Table 4.2, Row 9**)*
2. *Sum of (**Table 4.1, Row 2**) and (**Row 1**)*
3. *(**Row 2**) * (**Table 4.2, Row 5**)*
4. *Taken as the payment per period (PMT) for an average interest rate of 10% over 20 years, with the present value from (**Table 4.1, Row 3**), * (20 average years of life) / (2,144,836 lifetime kilometres from **Chapter 3**).*
5. *Calculated as change in C-Tax price from base (**Table 4.1, Row 1**) * (**Table 4.2, Row 9**)*
6. *Sum of (**Table 4.1, Row 8**) and (**Row 5**)*
7. *(**Row 6**) * (**Table 4.2, Row 5**)*
8. *Taken as the payment per period (PMT) for an average interest rate of 10% over 20 years, with the present value from (**Table 4.1, Row 3**), * (20 average years of life) / (2,144,836 lifetime kilometres from **Chapter 3**).*

*9. Sum of assumed costs from **Table 4.1** (**Row 14** + **Row 15** + **Row 16**)*
*10. (**Row 9**) * (**Table 4.2, Row 25**)*
*11. Taken as the payment per period (PMT) for an average interest rate of 10% over 20 years, with the present value from (**Table 4.1, Row 17**), * (20 average years of life) / (2,144,836 lifetime kilometres from **Chapter 3**).*

## 4.4 Results and Discussion

### 4.4.1 Total Cost of Alberta's Future LH Freight

With the per-kilometre values for the three components of total cost of ownership (fuel costs, vehicle capital expenditure, and IMAL costs) calculated, they can now be combined to generate the total per-kilometre values for the FCEVs in the NZ scenario, as well as for the ICEVs in the BAU and NZ scenarios, seen below in **Fig. 4.8**.

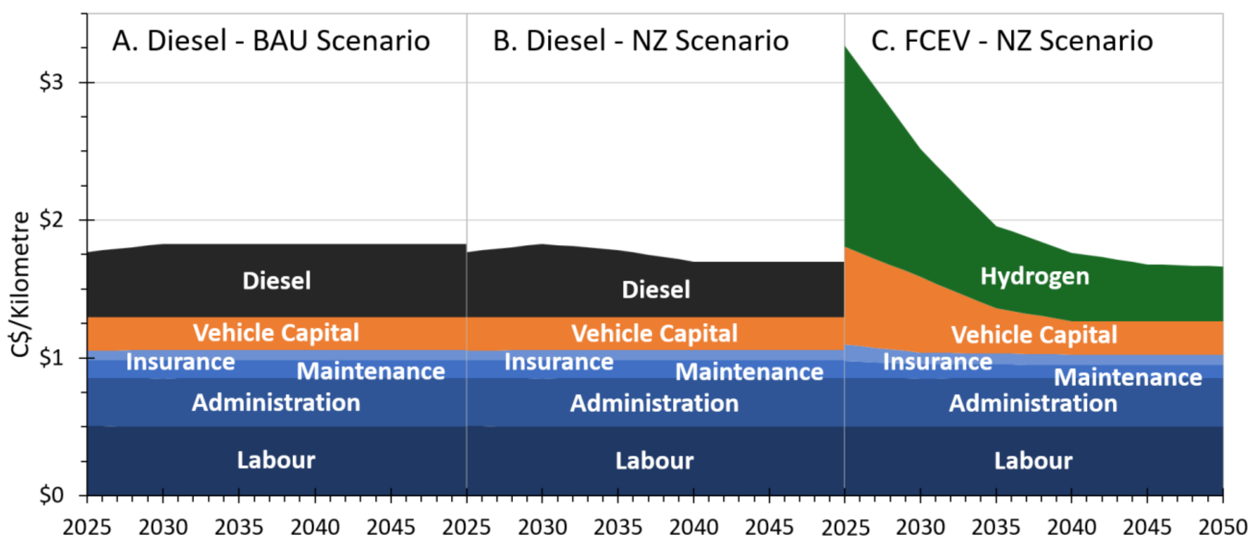



**Fig. 4.8.** Projected Total Cost of Ownership (TCO) for Diesel Internal Combustion Engine Vehicles (ICEV) in the Business-as-Usual (BAU) Scenario (**A**), Net-Zero (NZ) Scenario (**B**), and for Hydrogen Fuel Cell Electric Vehicles (FCEV) in the NZ Scenario (**C**).
*The figure shows the breakdown of total cost of ownership per kilometre for heavy-duty trucks in Alberta, with the price of diesel/hydrogen fuel on top, followed by the vehicle capital expenditure per kilometre in orange, and the various other per kilometre vehicle costs including insurance, maintenance, administration, and labour in different shades of blue.*

Studies such as the "*The Future of Freight Part A: Understanding the System*" (Lof and Layzell, 2019) estimate that heavy-duty diesel vehicles in North America have a TCO of CAD 1.75 per kilometre for carriers to operate and keep them on the road. The breakdown of component costs shown in **Fig 4.2** supports this, with both ICEV scenarios ranging between CAD 1.70 and CAD 1.85 per kilometre. Notably, labour and fuel account for the largest portions of the total cost of ownership. While the cost of labour should be consistent across the sector, this indicates that the cost of fuel plays a large part in the projected cost of vehicle ownership.

For the ICEV scenarios, the cost of diesel increases initially by approximately CAD 0.06 per kilometre (**Table 4.3**), as carbon taxes rise from CAD 95/t $CO_2$e in 2025 to CAD 170/t $CO_2$e in 2030. With reduced demand for diesel in the NZ scenario however, diesel costs decline (Canada Energy Regulator, 2023b) compared to the BAU scenario by CAD 0.45/litre, equivalent to CAD 0.13/km (**Fig. 4.8B, Fig. 4.8A**).

In the NZ scenario, FCEVs are projected to have a significantly higher TCO than diesel-ICEVs in 2025, driven by a threefold increase in both vehicle and hydrogen fuel costs, as well as higher initial insurance and maintenance costs. While the CapEx for diesel HDVs is expected to remain constant across both the net-zero and BAU scenarios (**Table 4.1**, **Section 4.2.1**), the cost differentials for FCEVs are anticipated to decline rapidly as deployment increases. By 2039, the TCO for FCEVs is projected to fall below that of the BAU diesel scenario due to significant reductions in fuel and vehicle CapEx by this point. By 2045, the TCO for FCEVs drops below the NZ diesel scenario as well, with now 25% lower maintenance costs and fuel costs nearing parity.

To understand the broader implications of these TCO costs, the values from **Fig. 4.8** were applied to the projections of VKT by each vehicle type from Scenario 2A (**Table 4.2**), shown below in **Fig. 4.9**. This enables a comparative analysis between the BAU Scenario and the NZ Scenario, allowing for a comprehensive evaluation of the full cost transformation, mirroring the vehicle population changes projected in Scenario 2A.

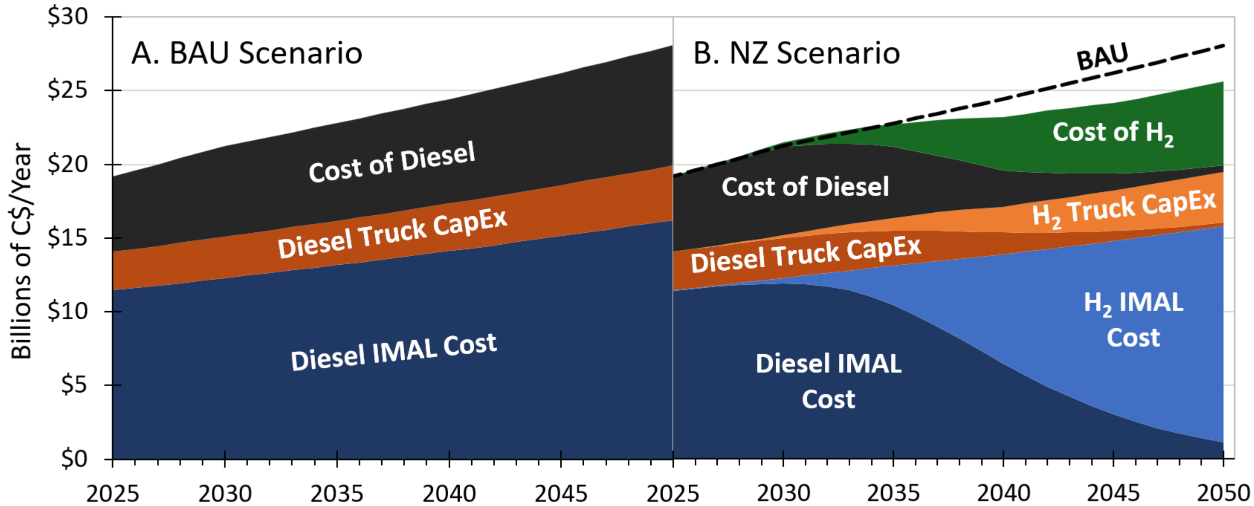



**Fig. 4.9.** Scenario Comparison of Total Costs Associated with Alberta's Freight Sector for Diesel ICEVs in the BAU Scenario (**A**), and All HDVs in the Net-Zero (NZ) Scenario (**B**).
*The figure shows the breakdown of total cost of ownership for heavy-duty trucks in Alberta, with the price of diesel/hydrogen fuel on top, followed by the new vehicle capital expenditure per kilometre in orange, and the various other per kilometre vehicle costs including insurance, maintenance, administration, and labour in blue. The darker shades of orange and blue in (B) indicate values for diesel within the NZ scenario.*

In the BAU scenario (**Fig. 4.9A**), the LH-HD trucking sector is projected to contribute CAD 19 billion to the economy in 2025, with growth reaching CAD 28 billion by 2050. In comparison, the transition to hydrogen-FCEVs in the NZ scenario shows a slight increase in expenditures from 2025 to 2035 (**Fig. 4.9B**), followed by lower projected costs to 2050, driven primarily by lower per-kilometre fuel costs in the NZ scenario (**Fig. 4.8B**). This results in a total discount of CAD ~2.5 billion within the NZ scenario through this transition.

In the NZ scenario, FCEVs are expected to reach a 25% market share by 2036, contributing CAD 6.54 billion that year. FCEVs will surpass diesel market share by 2040, coinciding with the expected FCEV cost parity, with FCEV total market share reaching CAD 12.76 billion and ICEV declining to CAD 10.43 billion. By 2050, FCEVs will represent 93% of the LH-HD market share, contributing CAD ~24 billion to the sector.

The overall decline in fuel costs, initially driven by diesel and later by hydrogen, highlights the significant role of fuel in this transition to net zero. By 2050, fuel costs will still account for 24% of total LH-HDV expenses, with CAD 2.0 billion out of the CAD 2.5 billion in total NZ savings attributed to fuel. The final delivered cost of hydrogen is projected to be CAD 6.00/kg by

2050, translating to a kilometre cost of CAD 0.40/km, CAD 0.13/km lower than diesel in the BAU scenario. However, these estimates do not factor in potential future government policies, such as a 'gas tax' for road infrastructure, which is currently included in diesel costs. If such a tax were applied to hydrogen, it could increase fuel costs for the net-zero transition, potentially reducing or even eliminating the expected savings.

### 4.4.2 Incremental Cost of FCEV Transition

Given that novel hydrogen-FCEVs are competing against a fully mature diesel-ICEV market, it is not surprising that the hydrogen-FCEV value chain will initially be more expensive. In the NZ scenario, incremental costs are projected to rise from CAD 38 million per year in 2025 to around CAD 500 million per year by 2034 (**Fig. 4.10A**), before declining to cost parity by 2040. These costs are primarily driven by the higher costs of hydrogen fuel and FCEVs, with the peak incremental cost of CAD 495 million in 2034 split almost equally between FCEV capital expenses and hydrogen fuel costs. As mentioned earlier, projected fuel costs do not fully account for a potential 'gas tax' for road infrastructure maintenance, which could increase the share of fuel costs in this incremental amount.

Expressed in per kilometre travelled (**Fig. 4.10A**), the incremental total cost of ownership in the NZ scenario would increase the TCO for the FCEV sector by approximately CAD 0.04/km, with an average maximum of about CAD 0.025/km for the entire LH-HDV sector. Understanding the impact of each financial component on the total value of the transition, including its sensitivity, is critical to ensuring a thorough evaluation.

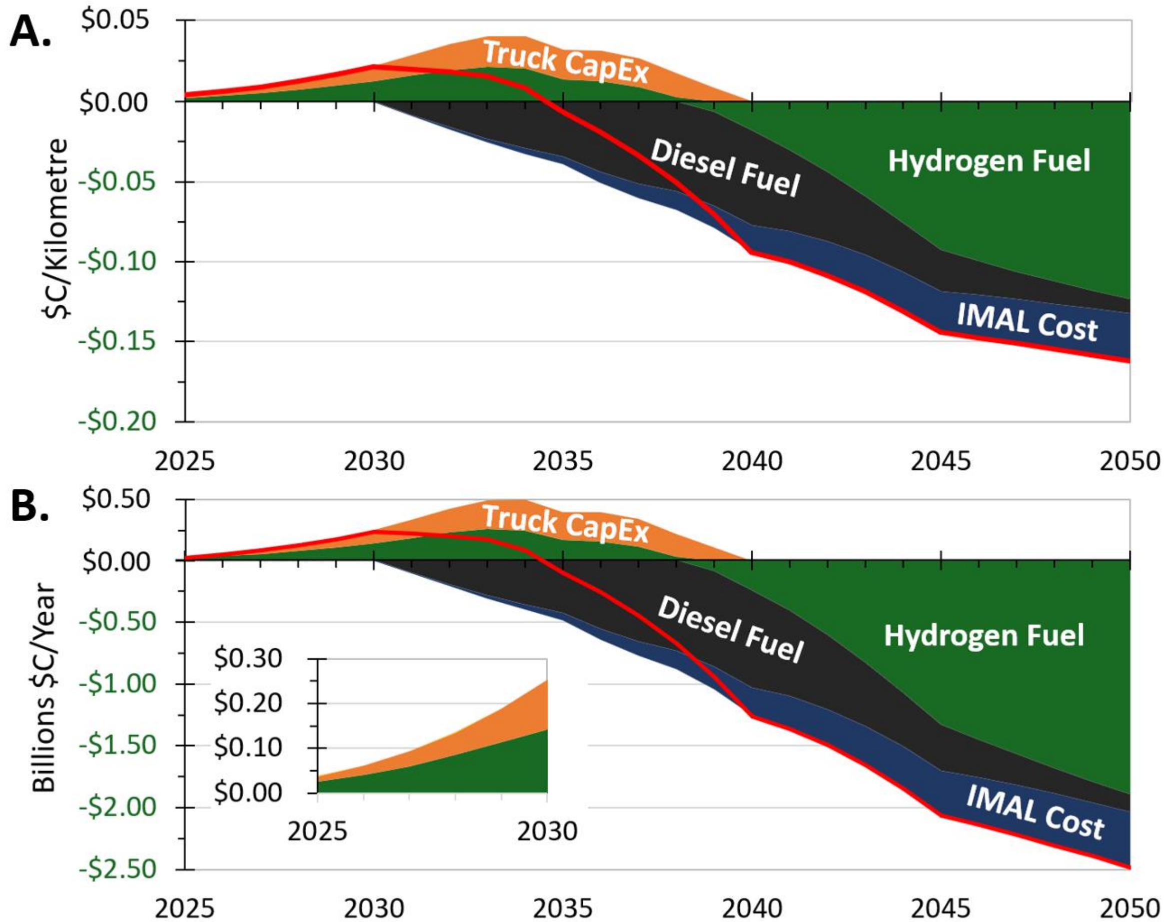



**Fig. 4.10.** Incremental TCO per Kilometre: BAU Scenario vs. Weighted NZ Scenario for Diesel-ICEVs and Hydrogen FCEVs **(A)**. Total Incremental TCO: BAU Scenario vs. Weighted NZ Scenario for Diesel-ICEVs and Hydrogen FCEVs **(B)**.
***4.10A*** *compares the total cost of ownership (TCO) per kilometre between the diesel BAU and NZ scenarios, with the NZ TCO weighted by the total kilometres driven for both diesel and hydrogen vehicles.* ***4.10B*** *compares the TCO between the diesel BAU and NZ scenarios, similarly weighted for total kilometres driven. The truck CapEx and IMAL (insurance, maintenance, administration, and labour) costs remain consistent between the BAU diesel and NZ diesel scenarios. Changes in fuel costs between the BAU and NZ scenarios are reflected, showing the impact of both diesel and hydrogen fuel.*

Fuel costs under the NZ scenario show significant savings compared to the BAU, with overall cost parity reached just before 2035 (**Fig. 4.10, Red Line**). This reduction has a substantial impact on TCO savings; however, it is important to note that reaching TCO cost parity by 2035 does not offset the ongoing FCEV CapEx costs which persist until 2040. Like fuel cost reductions, FCEV CapEx costs will directly affect truck buyers' ability to purchase new ZEVs, with incremental costs for FCEV CapEx by 2035 estimated at CAD 226 million. This indicates that support for the purchasing of new FCEVs must continue to 2040 at the earliest, to ensure continued adoption by industry. Nevertheless, the transition is projected to result in overall savings of CAD 2.5 billion, underscoring the need to understand both incremental costs and the influence of diesel price reductions.

While insurance and maintenance costs are initially higher for new fuel cell electric vehicles, their impact on the overall TCO for the HDV sector is minimal due to the small population of new vehicles. Over time, as these costs gradually decrease, they will lead to long-term savings for ZEVs, about 18% of total savings by 2050. It is important to consider how even slight differences in CAD/km could evolve, as minor changes can have significant impacts when multiplied by the billions of kilometres travelled annually by this sector.

### 4.4.3 GHG Emissions and Cost of Abatement

In the BAU scenario, life cycle GHG emissions from LH-ICEVs in Alberta are projected to rise from 11.7 Mt $CO_2$e/year in 2025 to 17 Mt $CO_2$e/year by 2050 (**Fig. 4.11A**, black line), an almost 45% increase in GHG emissions in just 25 years. In contrast, the NZ scenario forecasts an 86% reduction in GHG emissions from the BAU by 2050, declining just 2.3 Mt $CO_2$e/year, providing cumulative reductions of over 150 Mt $CO_2$e by 2050 (**Fig. 4.11B**).

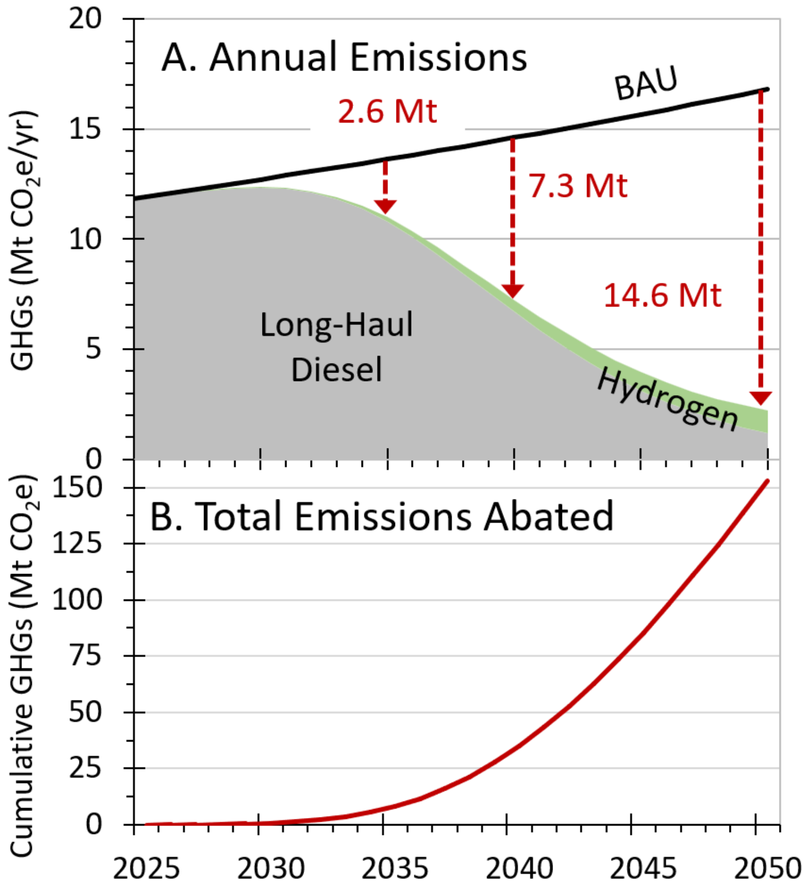



**Fig. 4.11.** Modelled GHG Emissions for Net-Zero Long-Haul Trucks in Alberta vs. Business-as-Usual (BAU) Scenario (**A**), and Cumulative Net-Zero Emissions Abated (**B**).
*The declining GHGs are shown in comparison to the BAU scenario, modelled by the red line, allowing for a comparison of GHG reduction between Scenario 2A, indicated by the values in red for 2035, 2040, and 2050.*

Hydrogen offers a substantial emission reduction potential of 153 Mt $CO_2e$ by 2050 - equivalent to taking approximately 2.9 million LDVs off the road for a year (Natural Resources Canada, 2023a) - and produces no emissions during fuel cell operation. However, current blue hydrogen production still generates notable GHG emissions. In the NZ scenario, hydrogen production is projected to account for 45% of the remaining LH-HDV emissions by 2050 (**Fig. 4.11A**), or roughly one megatonne of $CO_2e$ per year. This highlights the need to address future blue hydrogen emissions, particularly given the absence of GHG taxation on hydrogen fuel. This could involve strongly promoting green hydrogen, imposing taxes on FCEVs for proactive carbon removal, or taxing blue hydrogen production and refuelling stations.

Understanding the cumulative cost of the transition is crucial for both the government and industry, as it helps gauge the scale of the investment needed for this shift. When comparing cumulative emission reductions to the incremental costs of the transition (positive values in **Fig. 4.10A** summed to CAD 4 billion as shown in **Fig. 4.12A**), the cost of GHG abatement decreases significantly over time—from over CAD 3000/t $CO_2$e in 2025 to about CAD 26/t $CO_2$e by 2050 (**Fig. 4.12B**).

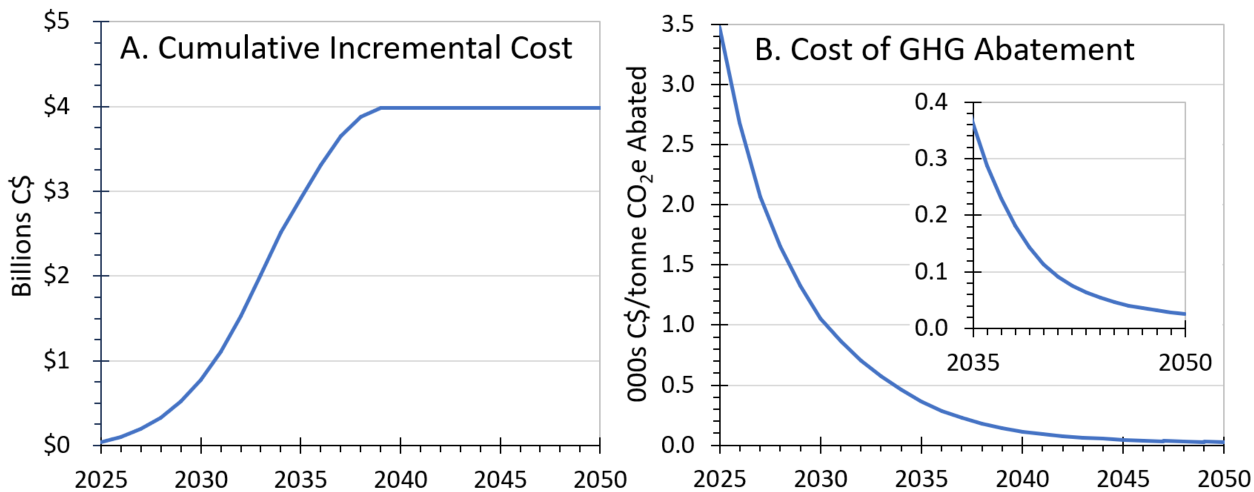



**Fig. 4.12** Cumulative Incremental Cost of NZ Transition **(A)**, and Cumulative Incremental Cost per Cumulative Tonne of $CO_2$e Abated **(B)**.
*Further description goes here:*

The inflated cost of abatement early in the transition is expected and should not discourage funding for the sector. This cost is not indicative of the overall value of transitioning to hydrogen and reducing GHGs; rather, it represents an additional benefit that will grow as the transition progresses. Estimates from the IEA in 2021 show that direct air carbon capture costs still vary widely, ranging from CAD 180 to CAD 465 per tonne of CO2 removed (Baylin-Stern and Berghout, 2021). By 2034, the cost of abatement in this transition falls just below the upper range of CAD 465, and by 2038, it aligns with the lower end at CAD 180. This suggests that within a decade, supporting this transition could become an even more cost-effective method for abating CO2 emissions. In the long run, the environmental and economic benefits will significantly outweigh the initial costs, further highlighting the value of this transition.

### 4.4.4 Funding Sources for Transition

This study clearly demonstrates the significant incremental costs associated with transitioning Alberta's LH-HD freight sector from a GHG-intensive diesel-ICEV value chain to a low-GHG hydrogen-FCEV value chain. Over the next 15 years, this transition is projected to require an investment of approximately CAD 4 billion (**Fig. 4.12A**).

Alberta's trucking sector cannot be expected to bear this additional cost to transition alone. External support will be necessary to ensure the industry's successful shift. Public entities, including federal and provincial governments, must provide financial, logistical, and regulatory assistance to facilitate the transition and mitigate risks for companies willing to lead the way. One potential source for the estimated CAD 4 billion needed over the next 15 years is carbon tax revenue.

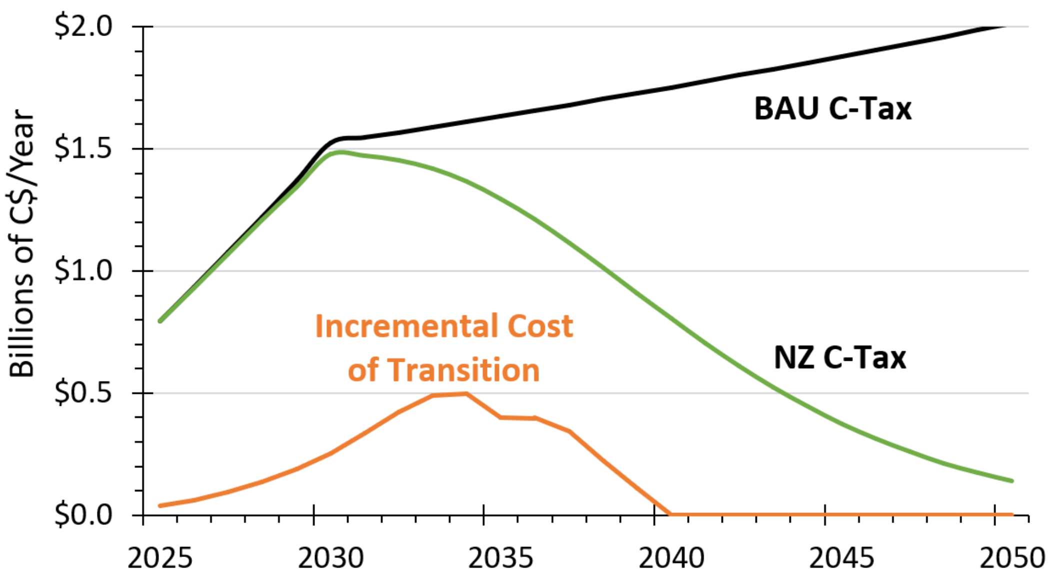



**Fig. 4.13.** Annual Canadian Carbon Tax Collected for the BAU and NZ Scenarios, Compared to the Incremental Cost to Offset the Transition.
*Extra information goes here.*

In 2024, diesel fuel in Alberta is subject to a carbon tax of CAD 80/t $CO_2e$ on tailpipe emissions, set to increase to CAD 95/t $CO_2e$ in 2025 and CAD 170/t $CO_2e$ by 2030 (**Table 4.1, Row 1**, and **Table 4.3, Row 1**).

When applied to the diesel consumed by the sector, the LH-HDV sector is expected to generate approximately CAD 800 million per year in 2025, increasing to CAD 1.4 billion/year by 2030. Assuming no further tax hikes after 2030, tax revenue would continue to grow under the BAU scenario to CAD 2 billion/year but would decline to CAD 141 million/year under the NZ scenario due to reduced diesel consumption (**Fig. 4.13**). Compared to these amounts, the incremental cost of the NZ transition is only a fraction of the carbon tax revenue (**Fig. 4.13,** red line), peaking at just 36% of the revenue in the NZ scenario. This suggests that carbon tax revenue could be a major driver of change in the industry, and even if the incremental cost of the transition were doubled, it would still account for less than 75% of the carbon tax revenue collected from these vehicles.

However, this assumes that the government will allocate carbon tax revenue to support the transition, rather than its current priorities of consumer rebates, small business tax reductions, and other programs (Maclean, 2019). Since the use of carbon tax funds can change with different governments, relying solely on this revenue may be overly optimistic. It will be crucial to secure multiple funding sources, including contributions from organizations or individuals with a vested interest in the transition, to ensure a critical lack of funding does not occur.

### 4.4.5 Economic Sensitivity Analysis

Understanding the key variables and sensitivities in this economic analysis can highlight its implications for future government and industry, while also revealing its limitations and the uncertainties in predicting the future of this transition. Examining these sensitivities across the value chain will help identify the areas most vulnerable to future changes and guide future research in this sector.

The first sensitivity, as discussed in **Section 3.5.1**, concerns the reliability of government data on fuel efficiency (L/100 km) and VKT/veh/yr. Government values for vehicles on the road, and fuel consumed by the sector are confirmed to be based on collected data, with an internally consistent model created to determine VKT based off fuel efficiency assumptions (Statistics Canada, personal communication). Discrepancies between government fuel efficiency assumptions and real-world observations suggest that government VKT/veh/yr figures are overestimated, resulting in inflated VKT values and thus total TCO calculations for this model.

This implies that the industry's overall modelled economic impact, in terms of total CAD and potential savings based on VKT, may be up to 27% lower than projected. This is given from previous studies that suggest the average efficiency is closer to 39.50 L/100km (Natural Resources Canada, 2000) than the 28.66 L/100km given by government. However, overestimating costs would also mean that incremental costs faced by the industry may be less than anticipated, potentially increasing the available funds for supporting the transition as the modelled carbon tax revenue is not based on VKT, but on fuel emissions.

Going into the **Chapter 4** analysis starting with fuel production, fluctuations in future natural gas, electricity, and diesel prices will have significant impacts on the overall TCO and incremental costs of this transition. By 2050, fuel costs are projected to account for 24% of total LH-HDV expenses, with CAD 2.0 billion out of the CAD 2.5 billion in total NZ savings attributed to fuel (**Section 4.4.2**). These savings are primarily expected from declining diesel prices, coupled with lower blue hydrogen costs due to stable natural gas prices. However, recent volatility in diesel prices (**Fig. 4.2**) suggests that further investigation into future diesel and natural gas pricing is needed to assess these costs more accurately. If diesel and natural gas prices rise, green hydrogen could become more competitive with blue hydrogen. Still, green hydrogen faces its own pricing challenges, as an increase in electricity prices from CAD 20 to CAD 100/MWh could raise production costs by 2-3 times regardless of electrolyzer CapEx (Khan et al., 2022), warranting its own investigation.

For hydrogen transport, the progression of maturity for this technology is mapped out, but predicting the speed and challenges of this transition remains difficult. Political factors, particularly in later stages such as pipeline construction, will heavily influence progress. Efficient development will require strong coordination between government and industry. A similar challenge exists with the scalability of hydrogen refuelling stations, which also affects the overall transition cost. Early-stage small hydrogen stations face higher costs, with economic viability improving as station sizes grow (e.g., 16 $tH_2$/day stations projected by 2045). Scaling up hydrogen infrastructure is essential for achieving economies of scale and keeping costs manageable. However, without the same level of coordination as with hydrogen transport, excess costs could arise, placing additional financial strain on station owners, who typically operate with narrow margins.

Projecting the cost of future and novel FCEVs is inherently challenging. While this paper's economic analysis has made projections based on expected cost parity and initial vehicle prices, the market will evolve rapidly as production ramps up and new LH-FCEVs, like the LH-HDVs on the road today, enter production. FCEV costs are expected to decline as economies of scale improve and technology advances. However, more research, particularly local studies, are needed to better understand the future costs of manufacturing longer-range, higher GVWR FCEVs. This includes evaluating insurance and maintenance costs for LH-FCEVs as well, as these factors are critical for adoption by trucking companies but have not been thoroughly investigated.

Beyond inherent cost uncertainties, it is crucial to recognize the major support required for this industry to successfully transition. Without adequate backing, the transition could face significant challenges. Trucking companies cannot shoulder the incremental costs alone, so government and possibly alternative investors must provide financial and policy support. Government actions, such as adjusting their support for hydrogen or carbon taxing, will directly affect the affordability of hydrogen FCEVs. While the carbon tax on diesel fuel could offer a valuable source of revenue for the transition, relying solely on this tax is risky given shifting government priorities, and the industry must be prepared for this.

There is an urgent need for further research in this sector to ensure accuracy and predictability in achieving the transition to net-zero. Overall, this transition is feasible, but it will require preparation and support from both government and industry to succeed. Even in this high-hydrogen Scenario 2A where TCO costs - such as fuel prices, FCEV purchase prices, and insurance/maintenance - may be overestimated due to VKT discrepancies from government, a further doubling of all incremental costs would still only require 75% of the expected carbon tax revenue collected from this industry. This demonstrates that, despite potential price variances, the transition costs remain reasonable and manageable for the industry.

## 4.5 Conclusions

This economic analysis highlights the significant costs and complexities involved in decarbonizing Alberta's long-haul heavy-duty vehicle sector, particularly through the introduction of a hydrogen fuel cell electric vehicle value chain. Heavy-duty vehicles, especially long-haul trucks, are notoriously difficult and costly to decarbonize, providing value in this study for understanding the transition's financial and logistical requirements. The establishment of a new hydrogen-based value chain is crucial for Alberta's future, as LH-HDV operations play a pivotal role in the province's economy, and thus require major focus for this transition.

The economic analysis reveals that hydrogen-FCEVs have a higher initial TCO compared to ICEVs, driven by vehicle capital expenditures (CapEx) and hydrogen fuel costs. However, as production scales and technology advances, the TCO for FCEVs is projected to decrease significantly, falling below that of diesel vehicles in the BAU scenario by 2039, and in the NZ scenario by 2045. While reaching projected cost parity for fuel by 2035 is significant, it does not offset ongoing FCEV CapEx costs, which persist until 2040. This indicates that continued financial support for FCEV purchases will be necessary until at least 2040 to ensure widespread industry adoption.

Incremental costs in the NZ scenario are expected to rise from CAD 38 million per year in 2025 to near CAD 500 million by 2034, before declining to cost parity by 2040. The peak incremental cost in 2034 is split almost evenly between FCEV capital costs and hydrogen fuel expenses. Fuel costs play a critical role in this transition, accounting for 24% of total LH-HDV expenses by 2050, with CAD 2.0 billion of the total CAD 2.5 billion in expected NZ savings attributed to fuel. In the BAU scenario overall, the LH-HD trucking sector is projected to contribute CAD 19 billion to Alberta's economy in 2025, growing to CAD 28.1 billion by 2050. In contrast, the NZ scenario sees slightly higher expenditures between 2025 and 2035 but achieves lower total costs of CAD 25.6 billion by 2050. This reflects the economic impact of the transition, demonstrating that the incremental costs represent only a small fraction of the economic size of Alberta's trucking industry. As the sector grows, the NZ scenario offers long-term cost savings and improved competitiveness.

Although the high initial cost of carbon abatement from this transition is expected, it should not discourage investment, as not only is this just an additional benefit of this transition, but these costs will also decrease over time. Estimates from the IEA in 2021 show that direct air carbon capture costs range from CAD 180 to CAD 465 per tonne of $CO_2$ removed (Baylin-Stern and Berghout, 2021). By 2034, the cost of abatement in this transition falls just below the upper range of CAD 465, and by 2038 it aligns with the lower end at CAD 180, only declining further past this in the coming years. This suggests that within a decade, supporting this transition could become an even more cost-effective method for abating CO2 emissions than direct CCS.

In conclusion, the key findings from this study emphasize the necessity of government support to make this transition feasible. Public backing for hydrogen, hydrogen infrastructure, FCEV adoption, and overall policy coordination is critical for ensuring that hydrogen becomes a sustainable solution for Alberta’s freight industry. External support from governments and alternative investors will be crucial, as Alberta's trucking sector cannot bear these costs alone. Public financial, logistical, and regulatory assistance will be essential to mitigate risks and facilitate the transition. Without this support, the transition may be delayed, or the costs may become insurmountable for trucking companies to bear alone. Overall, this study provides an initial cost estimate, highlighting the challenges posed by various uncertainties in the analysis and helping to gauge the overall scale and sensitivity of the transition. Despite some uncertainties in the cost estimates, the incremental cost of the NZ transition represents only a fraction of the industry and the expected carbon tax revenue. Even if these incremental costs were doubled, they would still only amount to 75% of the carbon tax revenue. This demonstrates that, despite the higher initial costs, this transition will be economically viable with the proper support.

# 5. Conclusions

## 5.1 Research Summary

The primary goal of this thesis was to model ZEV scenarios for the transition of Alberta's heavy-duty trucking sector to net-zero GHG emissions by 2050, examining through this model the feasibility of achieving Canada's HD-ZEV sales targets of 35% by 2030 and 95% by 2040. The study focused on the logistical challenges of adopting FCEVs and BEVs, the economic challenges within a new hydrogen-based value chain, and overall aimed to provide a strategic roadmap for the decarbonisation of Alberta's heavy-duty trucking sector, highlighting its feasibility, economic implications, and potential policy directions.

The long-haul heavy-duty freight sector is crucial to Canada's economy, but it is also a significant source of GHG emissions due to diesel combustion in ICEVs. **Chapter 2** explored the current state of energy use and GHG emissions in Canada's transportation sector, focusing on heavy-duty freight. The literature review explored various pathways to achieving low and net-zero emissions through ICE improvements, electric drivetrains, and hydrogen as a low-GHG energy source. It analyzed Alberta's heavy-duty fleet's contribution to provincial GHG emissions and assessed hydrogen production and delivery for FCEVs. Based on current research and government and industry support, FCEVs and BEVs were identified as the most viable options for transition.

This study builds on previous research (**Chapter 3,** Redick et al., in review) which introduced a stock and flow model for Alberta's heavy-duty trucking sector, projecting long-term transitions to net-zero emissions through four different scenarios. The chapter included projections for HDV sales, vehicle registrations, and kilometres travelled, considering energy use and GHG emissions under business-as-usual and net-zero scenarios for the future of BEVs and FCEVs. The feasibility of meeting the 35% by 2030 government sales target was assessed to be challenging, alongside the infrastructure required to support this ZEV adoption. The model demonstrated that while the net-zero transition presents logistical challenges, the life cycle emissions savings and alignment with Canada's decarbonisation goals more than justify the effort, and under the Scenario 2A presented in the chapter where Canada only focusses on meeting the 95% by 2040 target, it could provide a reasonable pathway to emission reduction.

**Chapter 4** provided an economic analysis of transitioning Alberta's heavy-duty freight sector to a hydrogen-based value chain, which revealed a notably high initial TCO for FCEVs compared to diesel vehicles. However, as production scales and technology evolves, the TCO for FCEVs is projected to decrease significantly, anticipated to fall below the BAU-diesel scenario by 2039 and the NZ-diesel scenario by 2045. The analysis highlighted the critical role of fuel costs in this transition, projecting that fuel savings will constitute most of the total NZ savings by 2050. It also detailed the incremental costs of the transition, primarily driven by FCEV capital expenses and hydrogen fuel costs where significantly, the incremental cost of the NZ transition is only a small fraction of the carbon tax revenue generated by Alberta's trucking sector. Despite the substantial upfront costs, the analysis supports continued investment in the hydrogen transition, showing long-term savings from fuel and maintenance cost reductions and the substantial environmental benefits of lowered GHG emissions.

Overall, the transition of heavy-duty vehicles within Canada offers significant benefits for Alberta and the country, including emissions reduction, energy savings, and the possibility of substantial future cost savings. Although the incremental costs associated with this transition are considerable, they are modest compared to the expected carbon tax revenue which is anticipated to more than double the incremental costs, given the tax is not removed by future governments. The most critical factor ensuring the success of this transition is effective communication and collaboration between government and industry. This support must extend into the future in terms of policy, research, and financing to facilitate a smooth transition.

## 5.2 Major Findings and Applications

In **Chapter 3**, the federal target of having 35% of new HDV sales be zero-emission by 2030 is unlikely to be met, as Alberta's trucking sector would need to bring 370 to 450 new FCEVs and 110 to 200 new BEVs into service by 2027, and 1,650-2,020 FCEVs and 510-890 BEVs by 2030. This challenge is compounded by the fact that few of the currently available vehicles are suitable for Alberta's demanding conditions (loads, ranges, and winter temperatures), and the necessary infrastructure for BEVs and FCEVs is not yet in place. However, meeting only the federal target of 95% of new zero-emission HDV sales by 2040 in our Scenario 2 appears more feasible. This target would require Alberta's trucking sector to bring only 140 to 170 new FCEVs and 40 to 75 new BEVs into service by 2027 and 580-710 FCEVs and 180-310 BEVs by 2030, allowing more time to deploy zero-emission vehicles capable of meeting the freight sector's needs and develop the infrastructure required for low-GHG hydrogen production, storage, transport, and delivery. The next six years (2024-2030) will be critical for planning and initiating the rapid deployment of ZEVs and supporting infrastructure. This deployment has large applications in reducing GHG emissions however, with projected reductions of 51% by 2040 and 87% by 2050 even for Scenario 2.

In **Chapter 4**, current and projected cost estimates for the existing diesel-ICEV and new hydrogen-FCEV value chains were derived from the literature and combined with data on vehicle numbers, kilometres travelled, and fuel demand in Alberta from Scenario 2A. The projections indicate that, in 2025, the total cost per kilometre for hydrogen FCEVs in Alberta's long-haul HDV sector will be 1.9 times higher than that of diesel ICEVs, largely due to the higher initial costs of vehicles and hydrogen fuel. However, this cost disparity is expected to narrow by the late 2030s as economies of scale and technological advancements reduce the costs of hydrogen and FCEVs, providing large potential for applications of this technology in the HDV industry around this time. Alberta's LH-HDV sector is expected to grow from a CAD 19 billion industry in 2025 to CAD 27.5 billion by 2050 in the BAU scenario. During this time, the incremental cost of transitioning from diesel ICEVs to hydrogen FCEVs, compared to the BAU scenario, starts at CAD 54 million per year in 2025, peaks at CAD 500 million by 2035, and declines to zero by 2040. When the cumulative incremental cost of CAD 4 billion is divided by the greenhouse gas reductions achieved, the cost of emissions reduction is projected to fall significantly—from over CAD 3,000 per tonne of $CO_2$ equivalent (t $CO_2$e) in 2025 to approximately CAD 26 per t $CO_2$e by 2050.

Given these financial challenges, Alberta's LH-HDV sector is unlikely to shoulder the full cost of the transition alone, creating a compelling case for government support. Provincial and federal assistance will be essential to cover the incremental costs and mitigate risks tied to establishing a new hydrogen value chain. Alberta is well-positioned to produce cost-effective, low-GHG hydrogen due to its access to inexpensive natural gas and geological storage capacity for $CO_2$, providing massive applications to the hydrogen value chain and FCEVs for Alberta. Furthermore, federal carbon taxes on diesel are projected to generate CAD 700 million to CAD 1.5 billion annually by 2030, which should be more than sufficient to cover the transition's incremental costs. While several government backed hydrogen-FCEV pilot and demonstration projects are underway in Alberta and across Canada, a coordinated long-term strategy involving government and industry is necessary to achieve the 95% ZEV target by 2040. This will require engagement across the entire value chain, from fuel production and storage to transportation, fuelling stations, and vehicle demand, and offsetting additional costs compared to diesel ICEVs.

Beyond these major conclusions, further relevant implications and applications of this transition for the sector and broader industry are outlined below:

**Future of Natural Gas and Diesel in Scenario 2A:**

- **Blue Hydrogen Production Needs:** Alberta's blue hydrogen production will require 2–3 billion cubic metres of natural gas annually by 2040, increasing to 4–5 billion cubic metres by 2050. This represents only 4–5% of current natural gas production in Alberta, a small amount to retain for hydrogen production (Alberta Energy Regulator, 2024b). The primary concern, however, lies not in supply strain but in the 1,043 kt $CO_2e$ per year of GHG emissions projected by 2050 from this NG usage, accounting for 45% of remaining HDV emissions in Scenario 2A by 2050.
- **Projected Diesel Demand Reduction:** Currently in 2024, Alberta's HDV sector consumes approximately 3,270 ML of diesel annually. By 2040, this demand is projected to fall by 43% to 1,877 ML/year, declining further to 874 ML/year by 2045 and 329 ML/year by 2050. With Canada's roughly 8,900 diesel refuelling stations collectively delivering 18,260 ML annually, or 2.05 ML/year per station on average (Statistics Canada, 2024c), Alberta may see a decrease of around 680 stations delivering diesel by 2040, 1,150 by 2045, and 1,450 by 2050 as diesel demand continues to decline across the province.

**Future Industry Considerations:**

- **ZEV Tax to Match Diesel Tax:** Alberta's diesel sales currently generate approximately CAD 556 million annually in federal (CAD 0.04/litre) and provincial (CAD 0.13/litre) taxes, excluding carbon taxes (Natural Resources Canada, 2023c). This equates to about CAD 0.049/km in taxes for diesel HDVs in Alberta. To establish tax parity for ZEVs, a similar rate of CAD 0.05/km could be applied through telematics tracking of ZEV VKT. Alternatively, an estimated CAD 0.73/kg tax on hydrogen (based on 66.4 g $H_2$/km from **Table 3.1**) or CAD 0.04/kWh on electricity (based on 1.38 kWh e/km from **Table 3.1**) could be implemented but would be difficult to apply to specific HDVs. Adjustments for ZEV road wear, which is higher than ICEVs due to increased vehicle weight, should also be considered in future government tax policies.

- **Public Perception of Hydrogen:** Public concerns about hydrogen often stem from perceived risks, similar to those historically associated with nuclear energy (Hartmann et al., 2013). Negative perceptions are exacerbated by incidents like the Hindenburg disaster, as well as valid safety concerns such as hydrogen's wide flammability range in air (4% to 75%) and nearly invisible pale blue flame (Najjar, 2013), and the limited proven reliability of refuelling stations (Kurtz et al., 2020) or FCEVs under Canadian conditions. To shift public perception, widespread support beyond individual industry or government efforts will be essential, as expanding hydrogen infrastructure alone will not sufficiently address safety and reliability concerns.
- **Implications for Broader Diesel Transport:** The shift to net-zero emission transport with FCEVs and BEVs extends beyond just the scope of Alberta's HDVs examined in this thesis. The principle of "designing the vehicle for the route" will become increasingly important, as operational needs will dictate the optimal technology for long-term transition of the various existing diesel transport groups. This approach maximizes efficiency and reduces costs, a practice already evident in medium-duty vehicles supported by Canada's iMHZEV program (Transport Canada, 2022a), which favor BEVs over FCEVs due to lighter design requirements. Conversely, hydrogen-powered trains (such as those developed by the CPR (Stephens, 2022)) address strict range and refuelling needs beyond BEV capabilities (Nqodi et al., 2023), and large freight vessels are starting to examine hydrogen for extended range currently utilized with diesel as well (Van Hoecke et al., 2021). Cross-industry collaboration within ZEV technology, required infrastructure, and increased efficiencies will be crucial for advancing infrastructure and technology, and events like the Canadian Hydrogen Convention (DMG Events, 2024) should be supported to ensure this collaboration.

**Reaching Market Maturity:**

- **Impact of Autonomous Vehicles on FCEVs and BEVs:** Autonomous technology is expected to significantly impact the future of FCEVs and BEVs. Research suggests that autonomous HD-ZEVs offer energy savings in various operation scenarios (Sigle and Hahn, 2023), and integrating autonomous systems could enhance cost efficiency and reduce the number of range equivalent FCEVs needed for freight compared to BEVs (Lee et al., 2021). However, uncertainties remain as HD-ZEV development progresses, especially since current advancements in autonomous technology are more focused on HD-ICEVs than HD-ZEVs. This further indicates the need for coordinated industry and government efforts to properly incentivize these advancements to support HD-ZEV autonomy.

- **Rural Alberta and Specialty HDVs:** Scenario 2A projects that nearly 40,000 diesel HDVs will still be among us in Alberta by 2050, primarily in rural areas and for specialized HDVs. These vehicles are expected to be among the last to transition due to limited access to zero-emission technologies and fewer R&D efforts targeting this group (Bae et al., 2024). As noted in Chapter 2, these HDVs may benefit most from using greener fossil fuels like biodiesel to offset emissions in the interim. Similar to remote areas that still lack cell coverage in Alberta in 2024, rural regions may not see complete HDV transition to zero emissions until well beyond 2050, emphasizing the issue of equitable technology access across Alberta.

## 5.3 Key Limitations and Future Research

This study offers a comprehensive analysis of the transition to net-zero emissions in Alberta's heavy-duty vehicle sector. Within this thesis, several limitations exist that provide valuable insights for future research to be done in this area.

One of the key limitations identified in **Chapter 3** relates to the accuracy of government data, particularly in modelling the HDV population. The reliability of data on fuel efficiency (L/100 km) and the kilometres travelled per year by HDVs is critical for accurate projections. However, discrepancies in the available data, especially the L/100 km values which appear to be significantly lower than real-world observations, limit the precision of our model by influencing the VKT/year values for HDVs. This suggests that future research should prioritize the collection and analysis of more accurate and up-to-date data, potentially using telematics or other advanced monitoring technologies that provide real-world fuel consumption and vehicle usage patterns.

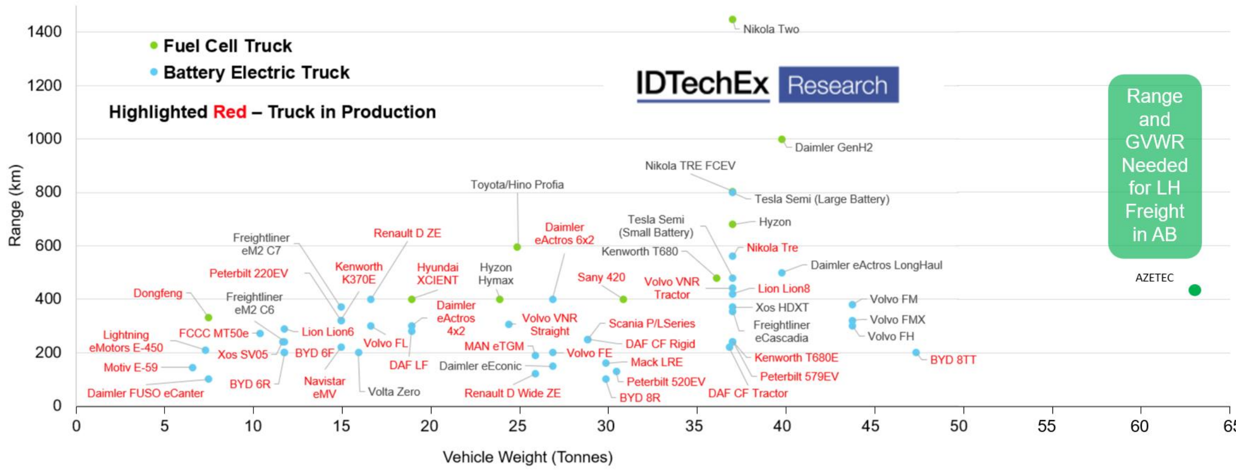



**Fig. 5.1.** 2023 Range and GVWR of existing heavy-duty FCEVs and BEVs in the HDV Market. *Figure sourced and adapted from IDTechEx Research (Siddiqi, 2023).*

In **Chapter 4**, a prominent limitation is the challenge of predicting future technologies. The rapid pace of technological change, coupled with the evolving market dynamics in the HDV sector, introduces uncertainty in the projections made in this study. This is evident in the wide variety of current FCEV's range and GVWR, both from vehicles in series production and still under development, as illustrated in **Fig. 5.1**. The difficulty in forecasting advancements in fuel cell technology, hydrogen production, and future diesel pricing, makes it challenging to accurately estimate future cost and performance estimations. A subsequent cost analysis is recommended once the market matures and costs stabilize, to provide a more precise cost outlook. Additionally, employing further financial scenario-based analyses could help model a spectrum of possible technological impacts on the HDV transition.

Additionally, the integration of up-to-date economic, environmental, and social factors into future models will be crucial for a more holistic understanding of the transition to net-zero emissions in the HDV sector. This includes examining the broader economic impacts, such as job creation or loss, and the social implications, such as equity and access to modern technologies across different regions. In conclusion, while this study provides valuable insights into the transition to a hydrogen-based HDV sector in Alberta, addressing these limitations through targeted future research will enhance the robustness of the findings and provide more actionable insights for policymakers and industry stakeholders.

# References

Ahluwalia, R.K., Roh, H.-S., Peng, J.-K., Papadias, D., Baird, A.R., Hecht, E.S., Ehrhart, B.D., Muna, A., Ronevich, J.A., Houchins, C., Killingsworth, N.J., Aceves, S.M., 2023. Liquid hydrogen storage system for heavy duty trucks: Configuration, performance, cost, and safety. International Journal of Hydrogen Energy 48, 13308–13323. https://doi.org/10.1016/j.ijhydene.2022.12.152

Ahmadi, P., Kjeang, E., 2015. Comparative life cycle assessment of hydrogen fuel cell passenger vehicles in different Canadian provinces. International Journal of Hydrogen Energy 40, 12905–12917. https://doi.org/10.1016/j.ijhydene.2015.07.147

Air Products, 2021. Air Products Announces Multi-Billion Dollar Net-Zero Hydrogen Energy Complex in Edmonton, Alberta, Canada [WWW Document]. URL https://www.airproducts.com/news-center/2021/06/0609-air-products-net-zero-hydrogen-energy-complex-in-edmonton-alberta-canada (accessed 6.23.22).

Air Products and Chemicals, Inc., 2023. Canada Net-zero Hydrogen Energy Complex. URL https://www.airproducts.com/energy-transition/canada-net-zero-hydrogen-energy-complex (accessed 1.16.24).

Alberta Energy Regulator, 2024a. Emerging Resources - Hydrogen. URL https://www.aer.ca/providing-information/data-and-reports/statistical-reports/st98/emerging-resources/hydrogen

Alberta Energy Regulator, 2024b. Natural Gas Production. URL https://www.aer.ca/providing-information/data-and-reports/statistical-reports/st98/natural-gas/production

Alberta Energy Regulator, 2023. Natural Gas Prices [WWW Document]. Alberta Energy Regulator. URL https://www.aer.ca/providing-information/data-and-reports/statistical-reports/st98/prices-and-capital-expenditure/natural-gas-prices (accessed 3.18.24).

Alberta Innovates, 2024. Alberta Innovates and Emissions Reduction Alberta Announce New Hydrogen Funding. URL https://albertainnovates.ca/news/alberta-innovates-and-emissions-reduction-alberta-announce-new-hydrogen-funding/

Alberta Innovates, 2023. Advancing Hydrogen – Competition 2. URL https://albertainnovates.ca/funding/advancing-hydrogen-competition-2/

Alberta Motor Transport Association, 2022. Hydrogen Commercial Vehicle Demonstrations. URL https://www.amta.ca/hydrogen-commercial-vehicle-demonstrations

Alonso-Villar, A., Davíðsdóttir, B., Stefánsson, H., Ásgeirsson, E.I., Kristjánsson, R., 2022. Technical, economic, and environmental feasibility of alternative fuel heavy-duty vehicles in Iceland. Journal of Cleaner Production 369, 133249. https://doi.org/10.1016/j.jclepro.2022.133249

Alternative Fuels Data Center, 2012. Types of Vehicles by Weight Class. URL https://afdc.energy.gov/data/10381

AMOGY Inc., 2024. Industries Amogy Supports: Heavy Duty Transportation. URL https://amogy.co/industries/

Anderegg, W.R.L., Trugman, A.T., Badgley, G., Anderson, C.M., Bartuska, A., Ciais, P., Cullenward, D., Field, C.B., Freeman, J., Goetz, S.J., Hicke, J.A., Huntzinger, D., Jackson, R.B., Nickerson, J., Pacala, S., Randerson, J.T., 2020. Climate-driven risks to the climate mitigation potential of forests. Science 368, eaaz7005. https://doi.org/10.1126/science.aaz7005

Anselma, P.G., Belingardi, G., 2022. Fuel cell electrified propulsion systems for long-haul heavy-duty trucks: present and future cost-oriented sizing. Applied Energy 321, 119354. https://doi.org/10.1016/j.apenergy.2022.119354

Appel, J., 2024. Pathways Alliance knows it can't back up its claims. National Observer.

Argonne National Laboratory, 2017. Heavy-Duty Refueling Station Analysis Model (HDRSAM).

Aronczyk, M., McCurdy, P., Russill, C., 2024. Greenwashing, net-zero, and the oil sands in Canada: The case of Pathways Alliance. Energy Research & Social Science 112, 103502. https://doi.org/10.1016/j.erss.2024.103502

Askin, A.C., Barter, G.E., West, T.H., Manley, D.K., 2015. The heavy-duty vehicle future in the United States: A parametric analysis of technology and policy tradeoffs. Energy Policy 81, 1–13. https://doi.org/10.1016/j.enpol.2015.02.005

Astiaso Garcia, D., 2017. Analysis of non-economic barriers for the deployment of hydrogen technologies and infrastructures in European countries. International Journal of Hydrogen Energy 42, 6435–6447. https://doi.org/10.1016/j.ijhydene.2017.01.201

Azolla Hydrogen Ltd., 2023. The AZ225 Biodrome. URL https://www.azollahydrogen.com/news/az225-unit-commission

Bae, Y., Rindt, C.R., Mitra, S.K., Ritchie, S.G., 2024. Fleet Operator Perspectives on Heavy-duty Vehicle Alternative Fueling Infrastructure. Transportation Research Record: Journal of the Transportation Research Board 2678, 490–506. https://doi.org/10.1177/03611981231171150

Bank of Canada, 2024. Inflation Calculator.

Basma, H., Zhou, Y., Rodríguez, F., 2022. Fuel-Cell Hydrogen Long-Haul Trucks in Europe: A Total Cost of Ownership Analysis. International Council on Clean Transportation.

Baylin-Stern, A., Berghout, N., 2021. IEA: Is carbon capture too expensive? URL https://www.iea.org/commentaries/is-carbon-capture-too-expensive

Blay-Roger, R., Bach, W., Bobadilla, L.F., Reina, T.R., Odriozola, J.A., Amils, R., Blay, V., 2024. Natural hydrogen in the energy transition: Fundamentals, promise, and enigmas. Renewable and Sustainable Energy Reviews 189, 113888. https://doi.org/10.1016/j.rser.2023.113888

Boretos, G.P., 2007. The future of the mobile phone business. Technological Forecasting and Social Change 74, 331–340. https://doi.org/10.1016/j.techfore.2005.11.005

Burke, A., 2020. Technology, Sustainability, and Marketing of Battery Electric and Hydrogen Fuel Cell Medium-Duty and Heavy-Duty Trucks and Buses in 2020-2040. https://doi.org/10.7922/G2H993FJ

Burke, A.F., Zhao, J., Miller, M.R., Sinha, A., Fulton, L.M., 2023. Projections of the costs of medium- and heavy-duty battery-electric and fuel cell vehicles (2020-2040) and related economic issues. Energy for Sustainable Development 77, 101343. https://doi.org/10.1016/j.esd.2023.101343

Burnham, A., Gohlke, D., Rush, L., Stephens, T., Zhou, Y., Delucchi, M., Birky, A., Hunter, C., Lin, Z., Ou, S., Xie, F., Proctor, C., Wiryadinata, S., Liu, N., Boloor, M., 2021. Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains (No. ANL/ESD-21/4, 1780970, 167399). https://doi.org/10.2172/1780970

Camuzeaux, J.R., Alvarez, R.A., Brooks, S.A., Browne, J.B., Sterner, T., 2015. Influence of Methane Emissions and Vehicle Efficiency on the Climate Implications of Heavy-Duty

Natural Gas Trucks. Environ. Sci. Technol. 49, 6402–6410. https://doi.org/10.1021/acs.est.5b00412
Canada Energy Regulator, 2023a. Provincial and Territorial Energy Profiles – Alberta.
Canada Energy Regulator, 2023b. Canada's Energy Future 2023: Energy Supply and Demand Projections to 2050.
Canada Energy Regulator, 2021. Towards Net-Zero: Electricity Scenarios. URL https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2021/towards-net-zero.html
Canada Revenue Agency, 2023. Fuel Charge Rates. URL https://www.canada.ca/en/revenue-agency/services/forms-publications/publications/fcrates/fuel-charge-rates.html#fcrts
Chauhan, S., Hans, M., Rittstieg, M., Zafar, S., 2023. Why the economics of electrification make this decarbonization transition different.
Courvoisier, T.J., European Academies Science Advisory Council, Deutsche Akademie der Naturforscher Leopoldina (Eds.), 2018. Negative emission technologies: what role in meeting Paris Agreement targets?, EASAC policy report. EASAC Secretariat, Deutsche Akademie der Naturforscher Leopoldina, Halle (Saale).
Cox, W.M., Alm, R., 2016. Onward and Upward! Bet on Capitalism - It Works. SMU Cox School of Business.
Cullen, D.A., Neyerlin, K.C., Ahluwalia, R.K., Mukundan, R., More, K.L., Borup, R.L., Weber, A.Z., Myers, D.J., Kusoglu, A., 2021. New roads and challenges for fuel cells in heavy-duty transportation. Nat Energy 6, 462–474. https://doi.org/10.1038/s41560-021-00775-z
Cunanan, C., Tran, M.-K., Lee, Y., Kwok, S., Leung, V., Fowler, M., 2021. A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles. Clean Technol. 3, 474–489. https://doi.org/10.3390/cleantechnol3020028
Daimler Truck, 2024. Safe, Fast and Simple: Daimler Truck and Linde Set New Standard for Liquid Hydrogen Refueling Technology. URL https://northamerica.daimlertruck.com/PressDetail/safe-fast-and-simple-daimler-truck-2024-02-07/
Daimler Truck North America LLC, 2024. Freightliner eCascadia. URL https://www.freightliner.com/trucks/ecascadia/
Davidson, R.B., Spalding, D.A.E., Harrison, R.O., Smith, P., 2024. Alberta. Encyclopedia Britannica. URL https://www.britannica.com/place/Alberta-province (accessed 9.13.24).
Department of Finance Canada, 2021. Investment Tax Credit for Carbon Capture, Utilization, and Storage. URL https://www.canada.ca/en/department-finance/programs/consultations/2021/investment-tax-credit-carbon-capture-utilization-storage.html
Dervisoglu, R., 2012. Diagram of a proton conducting solid oxide fuel cell.
DMG Events, 2024. Hydrogen Expo Home [WWW Document]. URL https://www.hydrogenexpo.com/home/ (accessed 10.29.24).
Edward Laity, 2024. Max Power discovers 96.4% natural hydrogen in Canada. URL https://www.h2-view.com/story/max-power-discovers-96-4-natural-hydrogen-in-canada/2113362.article/
El Hannach, M., Ahmadi, P., Guzman, L., Pickup, S., Kjeang, E., 2019. Life cycle assessment of hydrogen and diesel dual-fuel class 8 heavy duty trucks. International Journal of Hydrogen Energy 44, 8575–8584. https://doi.org/10.1016/j.ijhydene.2019.02.027

Emissions Reduction Alberta, 2024. Accelerating Hydrogen Challenge. URL https://www.eralberta.ca/funding-technology/accelerating-hydrogen-challenge/
Emissions Reduction Alberta, 2023. Alberta Zero Emission Hydrogen Transit. URL https://www.eralberta.ca/projects/details/alberta-zero-emission-hydrogen-transit-azeht/
Environment and Climate Change Canada, 2023. National Inventory Report (NIR) – 2023 Edition.
Environment and Climate Change Canada, 2022a. 2030 emissions reduction plan: Canada's next steps to clean air and a strong economy. Environment and Climate Change Canada = Environnement et changement climatique Canada, Gatineau, QC.
Environment and Climate Change Canada, 2022b. Canada launches consultations on a Clean Electricity Standard to achieve a net-zero emissions grid by 2035. Canada.ca. URL https://www.canada.ca/en/environment-climate-change/news/2022/03/canada-launches-consultations-on-a-clean-electricity-standard-to-achieve-a-net-zero-emissions-grid-by-2035.html
Environment and Climate Change Canada, 2022c. Canada releases Faster and Further: Canada's Methane Strategy. URL https://www.canada.ca/en/environment-climate-change/news/2022/09/canada-releases-faster-and-further-canadas-methane-strategy2.html
European Hydrogen Backbone, 2024. The European Hydrogen Backbone (EHB) initiative. URL https://ehb.eu (accessed 7.18.24).
Ford, J.D., Couture, N., Bell, T., Clark, D.G., 2018. Climate change and Canada's north coast: research trends, progress, and future directions. Environ. Rev. 26, 82–92. https://doi.org/10.1139/er-2017-0027
Ford Motor Company, 2024. 2024 Super Duty® F-450® Limited. URL https://www.ford.ca/trucks/super-duty/models/f450-limited/ (accessed 8.17.24).
Forrest, K., Mac Kinnon, M., Tarroja, B., Samuelsen, S., 2020. Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California. Applied Energy 276, 115439. https://doi.org/10.1016/j.apenergy.2020.115439
Gallagher, J., 2023. Emissions from natural hydrogen. Nat Energy 8, 774–774. https://doi.org/10.1038/s41560-023-01344-2
Global News, Toy, A., 2024. Alberta adds new EV tax, increases land titles levy in 2024 budget. Consumer News.
Government of Alberta, 2023a. Alberta population estimates : data tables.
Government of Alberta, 2023b. Carbon Offset Emission Factors Handbook Version 3.1, Version 3.1. ed. Alberta Environment and Protected Areas, Edmonton, Alberta.
Government of Alberta, 2022. Hydrogen development – Overview. URL https://www.alberta.ca/hydrogen-development-overview
Government of Alberta, 2021a. Alberta Hydrogen Roadmap.
Government of Alberta, 2021b. Carbon capture, utilization and storage [WWW Document]. URL https://www.alberta.ca/carbon-capture-and-storage.aspx (accessed 5.29.21).
Government of Alberta, 2020. Oil Sands Emissions Limit Act.
Government of Canada, 2022. On-Road Vehicle and Engine Emission Regulations (SOR/2003-2).
Government of Canada, 2021. Canadian Net-Zero Emissions Accountability Act. S.C. 2021, c. 22.
Graham, L.A., Rideout, G., Rosenblatt, D., Hendren, J., 2008. Greenhouse gas emissions from heavy-duty vehicles. Atmospheric Environment 42, 4665–4681. https://doi.org/10.1016/j.atmosenv.2008.01.049
Gray, N., O'Shea, R., Wall, D., Smyth, B., Lens, P.N.L., Murphy, J.D., 2022. Batteries, fuel cells, or engines? A probabilistic economic and environmental assessment of electricity and

electrofuels for heavy goods vehicles. Advances in Applied Energy 8, 100110. https://doi.org/10.1016/j.adapen.2022.100110
Hartmann, P., Apaolaza, V., D'Souza, C., Echebarria, C., Barrutia, J.M., 2013. Nuclear power threats, public opposition and green electricity adoption: Effects of threat belief appraisal and fear arousal. Energy Policy 62, 1366–1376. https://doi.org/10.1016/j.enpol.2013.07.058
Healy, C., Bressers, A., 2024. China's slowdown is weighing on the outlook for global oil demand growth. URL https://www.iea.org/commentaries/china-s-slowdown-is-weighing-on-the-outlook-for-global-oil-demand-growth?utm_campaign=IEA+newsletters&utm_medium=Email&utm_source=SendGrid
Hegde, S., Bonfitto, A., Castellanos Molina, L.M., 2023. Electric Machine and Battery Sizing for Hybrid Electric Heavy Duty Vehicles, in: Volume 1: 25th International Conference on Advanced Vehicle Technologies (AVT). Presented at the ASME 2023 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, Boston, Massachusetts, USA, p. V001T01A007. https://doi.org/10.1115/DETC2023-114898
Hipkins, R., Cowie, B., 2016. The sigmoid curve as a metaphor for growth and change. tandc 16. https://doi.org/10.15663/tandc.v16i2.136
HPDI Technology, 2024. H2 HPDI. URL https://www.hpditechnology.com/h2-hpdi/
Hunter, C., Penev, M., Reznicek, E., Lustbader, J., Birky, A., Zhang, C., 2021. Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks (No. NREL/TP-5400-71796, 1821615, MainId:6232). https://doi.org/10.2172/1821615
Hydrogen Council, 2020. Path to Hydrogen Competitiveness: A Cost Perspective.
Hyundai Motor Company, 2024. XCIENT Fuel Cell Truck. URL https://ecv.hyundai.com/global/en/products/xcient-fuel-cell-truck-fcev
ICF International, 2019. Comparison of Medium- and Heavy-Duty Technologies in California.
IEA, 2022. World Energy Outlook 2022.
INRS, 2024. Natural hydrogen: first reports are released on the potential of this emerging resource. URL https://inrs.ca/en/news/natural-hydrogen-first-reports-are-released-on-the-potential-of-this-emerging-resource/
International Council on Clean Transportation, 2014. Heavy-Duty Vehicle Diesel Engine Efficiency Evaluation and Energy Audit.
International Council on Clean Transportation, Basma, H., Buysse, C., Yuanrong, Z., Rodriguez, F., 2023. Total Cost of Ownership of Alternative Powertrain Technologies for Class 8 Long-Haul Trucks in the United States. International Council on Clean Transportation.
International Energy Agency, 2020. Cross-cutting: Hydrogen.
ISO, 2018a. ISO 19881:2018 Gaseous hydrogen — Land vehicle fuel containers.
ISO, 2018b. ISO 19882:2018 Gaseous hydrogen — Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers.
Jovan, D.J., Dolanc, G., 2020. Can Green Hydrogen Production Be Economically Viable under Current Market Conditions. Energies 13, 6599. https://doi.org/10.3390/en13246599
Kalibrate Canada Inc., 2023. Canadian 2022 National Retail Petroleum Site Census — Executive summary.
Kenworth Truck Company, 2024. T680 FUEL CELL ELECTRIC VEHICLE. URL https://www.kenworth.com/trucks/t680-fcev/

Khan, M.A., MacKinnon, C., Young, C., Layzell, D.B., 2022. Techno-Economics of a New Hydrogen Value Chain Supporting Heavy Duty Transport. The Transition Accelerator.

Korányi, T.I., Németh, M., Beck, A., Horváth, A., 2022. Recent Advances in Methane Pyrolysis: Turquoise Hydrogen with Solid Carbon Production. Energies 15, 6342. https://doi.org/10.3390/en15176342

Kpekou, R., Nahornick, N., Scholz, T., 2024. Investment Tax Credit for Clean Hydrogen. URL https://www.pbo-dpb.ca/en/publications/LEG-2324-021-S--investment-tax-credit-clean-hydrogen--credit-impot-investissement-hydrogene-propre

Kurtz, J., Sprik, S., Peters, M., Bradley, T.H., 2020. Retail Hydrogen Station Reliability Status and Advances. Reliability Engineering & System Safety 106823. https://doi.org/10.1016/j.ress.2020.106823

Lajevardi, S.M., Axsen, J., Crawford, C., 2022. Simulating competition among heavy-duty zero-emissions vehicles under different infrastructure conditions. Transportation Research Part D: Transport and Environment 106, 103254. https://doi.org/10.1016/j.trd.2022.103254

Lang, J., 2023. NET ZERO EMISSIONS RACE [WWW Document]. Energy & Climate Intelligence Unit. URL https://eciu.net/netzerotracker

Layzell, D.B., Cunningham, Z., Shiran, H.S., Kheirabadi, A.C., In press. A Role for Canadian Oil and Gas in the Net-Zero Transition: An NZEST Model Scenario (No. Vol. 6, Issue 2). Transition Accelerator Reports.

Layzell, D.B., Lof, J., McElheran, K., Narendran, M., Belanger, N., Straatman, B., Sit, S., 2020a. The Future of Freight Part C: Implications for Alberta of Alternatives to Diesel.

Layzell, D.B., Lof, J., Young, C., Leary, J., 2020b. Building a Transition Pathway to A Vibrant Hydrogen Economy In The Alberta Industrial Heartland.

Layzell, D.B., Millington, D., Lee, R., 2023. Towards a Fuel Hydrogen Economy in the Calgary Region: A Feasibility Study (No. Volume 5, Issue 1.).

Layzell, D.B., Young, C., Lof, J., Leary, J., 2020c. Towards Net-Zero Energy Systems in Canada: A Key Role for Hydrogen. The Transition Accelerator.

Ledna, C., Muratori, M., Yip, A., Jadun, P., Hoehne, C., 2022. Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis (No. NREL/TP-5400-82081, 1854583, MainId:82854). https://doi.org/10.2172/1854583

Lee, U., Jeon, S., Lee, I., 2021. Shared Autonomous Vehicle System Design for Battery Electric Vehicle (BEV) and Fuel Cell Electric Vehicle (FCEV), in: Volume 3B: 47th Design Automation Conference (DAC). Presented at the ASME 2021 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, Virtual, Online, p. V03BT03A029. https://doi.org/10.1115/DETC2021-67734

Li, J., Zhang, J., Zhao, Z., 2020. Analysis of Rapid Demand Variation in Electric Vehicle Industry based on Innovation Diffusion Theory. IOP Conf. Ser.: Earth Environ. Sci. 619, 012065. https://doi.org/10.1088/1755-1315/619/1/012065

Li, S., Djilali, N., Rosen, M.A., Crawford, C., Sui, P., 2022a. Transition of heavy-duty trucks from diesel to hydrogen fuel cells: Opportunities, challenges, and recommendations. Intl J of Energy Research 46, 11718–11729. https://doi.org/10.1002/er.8066

Li, S., Djilali, N., Rosen, M.A., Crawford, C., Sui, P., 2022b. Transition of heavy-duty trucks from diesel to hydrogen fuel cells: Opportunities, challenges, and recommendations. Intl J of Energy Research 46, 11718–11729. https://doi.org/10.1002/er.8066

Liao, F., Molin, E., Timmermans, H., Van Wee, B., 2019. Consumer preferences for business models in electric vehicle adoption. Transport Policy 73, 12–24. https://doi.org/10.1016/j.tranpol.2018.10.006

Lof, J., Layzell, D., 2019. The Future of Freight Part A: Understanding the System. CESAR Scenarios.

Lof, J., McElheran, K., Narendran, M., Belanger, N., Straatman, B., Sit, S., Layzell, D.B., 2019. The Future of Freight Part B: Assessing Zero Emission Diesel Fuel Alternatives for Freight Transportation in Alberta (No. CESAR Scenarios Vol 4, Issue 2: 1-62).

Maclean, R., 2019. Alberta's carbon tax brought in billions. See where it went.

Mahajan, D., Tan, K., Venkatesh, T., Kileti, P., Clayton, C.R., 2022. Hydrogen Blending in Gas Pipeline Networks—A Review. Energies 15, 3582. https://doi.org/10.3390/en15103582

Marchetti, C., 1991. Modeling Innovation Diffusion Forecasting technological innovation, pp.55–77.

Mareev, I., Becker, J., Sauer, D., 2017. Battery Dimensioning and Life Cycle Costs Analysis for a Heavy-Duty Truck Considering the Requirements of Long-Haul Transportation. Energies 11, 55. https://doi.org/10.3390/en11010055

McKenzie, L.R., Lee, D., Amoako-Attah, J., 2023. Analysis of Hydrogen Production Methods Using the Analytic Hierarchy Process. Engineering Future Sustainability 1. https://doi.org/10.36828/efs.206

Meikle, G., Gray, M., Van Den Assem, D., Ghazar, C., Parent, D., Emissions Reduction Alberta and Alberta Innovates, 2024. Alberta's Low-Carbon Hydrogen Production: How Low Can It Go?

Najjar, Y.S.H., 2013. Hydrogen safety: The road toward green technology. International Journal of Hydrogen Energy 38, 10716–10728. https://doi.org/10.1016/j.ijhydene.2013.05.126

Natali, S.M., Holdren, J.P., Rogers, B.M., Treharne, R., Duffy, P.B., Pomerance, R., MacDonald, E., 2021. Permafrost carbon feedbacks threaten global climate goals. Proc. Natl. Acad. Sci. U.S.A. 118, e2100163118. https://doi.org/10.1073/pnas.2100163118

Natural Resources Canada, 2023a. Comprehensive Energy Use Database.

Natural Resources Canada, 2023b. Types of zero-emission vehicles. URL https://natural-resources.canada.ca/energy-efficiency/transportation-alternative-fuels/types-zero-emission-vehicles/25048

Natural Resources Canada, 2023c. Fuel Consumption Levies in Canada. URL https://natural-resources.canada.ca/our-natural-resources/domestic-and-international-markets/transportation-fuel-prices/fuel-consumption-taxes-canada/18885

Natural Resources Canada, 2022. Electric Charging and Alternative Fuelling Stations Locator.

Natural Resources Canada, 2000. Fuel Efficiency Benchmarking in Canada's Trucking Industry. URL https://natural-resources.canada.ca/energy/efficiency/transportation/commercial-vehicles/reports/7607

Navas-Anguita, Z., García-Gusano, D., Dufour, J., Iribarren, D., 2021. Revisiting the role of steam methane reforming with CO2 capture and storage for long-term hydrogen production. Science of The Total Environment 771, 145432. https://doi.org/10.1016/j.scitotenv.2021.145432

Nikola Corporation, 2024. TRE FCEV. URL https://www.nikolamotor.com/tre-fcev

Nimana, B., Canter, C., Kumar, A., 2015. Life cycle assessment of greenhouse gas emissions from Canada's oil sands-derived transportation fuels. Energy 88, 544–554. https://doi.org/10.1016/j.energy.2015.05.078

Nqodi, A., Mosetlhe, T.C., Yusuff, A.A., 2023. Advances in Hydrogen-Powered Trains: A Brief Report. Energies 16, 6715. https://doi.org/10.3390/en16186715

Oni, A.O., Anaya, K., Giwa, T., Di Lullo, G., Kumar, A., 2022. Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. Energy Conversion and Management 254, 115245. https://doi.org/10.1016/j.enconman.2022.115245

Pardhi, S., Chakraborty, S., Tran, D.-D., El Baghdadi, M., Wilkins, S., Hegazy, O., 2022. A Review of Fuel Cell Powertrains for Long-Haul Heavy-Duty Vehicles: Technology, Hydrogen, Energy and Thermal Management Solutions. Energies 15, 9557. https://doi.org/10.3390/en15249557

Pearce, F., Yale, 2024. Natural Hydrogen: A Potential Clean Energy Source Beneath Our Feet. Yale Environment 360. URL https://e360.yale.edu/features/natural-geologic-hydrogen-climate-change

Peters, R., Breuer, J.L., Decker, M., Grube, T., Robinius, M., Samsun, R.C., Stolten, D., 2021. Future Power Train Solutions for Long-Haul Trucks. Sustainability 13, 2225. https://doi.org/10.3390/su13042225

Reichwein, T., 2022. Hydrogen Storage in Salt and Hard Rock Caverns. LANE POWER & ENERGY SOLUTIONS, INC.

Rohith, G., Devika, K.B., Menon, P.P., Subramanian, S.C., 2023. Sustainable Heavy Goods Vehicle Electrification Strategies for Long-Haul Road Freight Transportation. IEEE Access 11, 26459–26470. https://doi.org/10.1109/ACCESS.2023.3257431

Romano, M.C., Antonini, C., Bardow, A., Bertsch, V., Brandon, N.P., Brouwer, J., Campanari, S., Crema, L., Dodds, P.E., Gardarsdottir, S., Gazzani, M., Jan Kramer, G., Lund, P.D., Mac Dowell, N., Martelli, E., Mastropasqua, L., McKenna, R.C., Monteiro, J.G.M., Paltrinieri, N., Pollet, B.G., Reed, J.G., Schmidt, T.J., Vente, J., Wiley, D., 2022. Comment on "How green is blue hydrogen?" Energy Science & Engineering 10, 1944–1954. https://doi.org/10.1002/ese3.1126

Samsun, R., Rex, M., Antoni, L., Stolten, D., 2022. Deployment of Fuel Cell Vehicles and Hydrogen Refueling Station Infrastructure: A Global Overview and Perspectives. Energies 15, 4975. https://doi.org/10.3390/en15144975

Scheer, A., Schwarz, M., Hopkins, D., Caldecott, B., 2022. Whose jobs face transition risk in Alberta? Understanding sectoral employment precarity in an oil-rich Canadian province. Climate Policy 22, 1016–1032. https://doi.org/10.1080/14693062.2022.2086843

Schneider, J., Teichert, O., Zähringer, M., Balke, G., Lienkamp, M., 2023. The novel Megawatt Charging System standard: Impact on battery size and cell requirements for battery-electric long-haul trucks. eTransportation 17, 100253. https://doi.org/10.1016/j.etran.2023.100253

Sen, B., Ercan, T., Tatari, O., 2017. Does a battery-electric truck make a difference? – Life cycle emissions, costs, and externality analysis of alternative fuel-powered Class 8 heavy-duty trucks in the United States. Journal of Cleaner Production 141, 110–121. https://doi.org/10.1016/j.jclepro.2016.09.046

Sharpe, B., Basma, H., 2022. A meta-study of purchase costs for zero-emission trucks.

Shin, H.K., Ha, S.K., 2023. A Review on the Cost Analysis of Hydrogen Gas Storage Tanks for Fuel Cell Vehicles. Energies 16, 5233. https://doi.org/10.3390/en16135233

Siddiqi, S., 2023. Electric and Fuel Cell Trucks 2023-2043.

Sigle, S., Hahn, R., 2023. Energy Assessment of Different Powertrain Options for Heavy-Duty Vehicles and Energy Implications of Autonomous Driving. Energies 16, 6512. https://doi.org/10.3390/en16186512

Statistics Canada, 2024a. Population estimates, quarterly. https://doi.org/10.25318/1710000901-ENG

Statistics Canada, 2024b. Monthly average retail prices for gasoline and fuel oil, by geography. https://doi.org/10.25318/1810000101-ENG

Statistics Canada, 2024c. Sales of fuel used for road motor vehicles, annual. https://doi.org/10.25318/2310006601-ENG

Statistics Canada, 2010. 2000 - 2010. Canadian Vehicle Survey: Annual – ARCHIVED.

Statistics Canada, 1999. Archived - Road motor vehicle, trailer and snowmobile registration.

Stephens, B., 2022. Canadian Pacific's hydrogen-powered locomotive makes first revenue run.

Talaei, A., Gemechu, E., Kumar, A., 2020. Key factors affecting greenhouse gas emissions in the Canadian industrial sector: A decomposition analysis. Journal of Cleaner Production 246, 119026. https://doi.org/10.1016/j.jclepro.2019.119026

Tanvir, S., Un-Noor, F., Boriboonsomsin, K., Gao, Z., 2021. Feasibility of Operating a Heavy-Duty Battery Electric Truck Fleet for Drayage Applications. Transportation Research Record 2675, 258–268. https://doi.org/10.1177/0361198120957325

Tesla, 2024. Tesla Semi. URL https://www.tesla.com/semi

The Canadian Press, 2024. Pathways Alliance to apply for regulatory approval of $16.5B carbon capture project.

The Engineering ToolBox, 2003. Fuels - Higher and Lower Calorific Values.

Transport Canada, 2022a. Incentives for Medium- and Heavy-Duty Zero-Emission Vehicles Program (iMHZEV).

Transport Canada, 2022b. Canada's action plan for clean on-road transportation. Government of Canada = Gouvernement du Canada, Ottawa.

Van Hoecke, L., Laffineur, L., Campe, R., Perreault, P., Verbruggen, S.W., Lenaerts, S., 2021. Challenges in the use of hydrogen for maritime applications. Energy Environ. Sci. 14, 815–843. https://doi.org/10.1039/D0EE01545H

Volvo Penta, 2023. Exploring hydrogen engine advantages: Volvo Penta insights. URL https://www.volvopenta.com/about-us/news-page/2023/sep/exploring-hydrogen-engine-advantages-volvo-penta-insights/

Walsh, J.E., Ballinger, T.J., Euskirchen, E.S., Hanna, E., Mård, J., Overland, J.E., Tangen, H., Vihma, T., 2020. Extreme weather and climate events in northern areas: A review. Earth-Science Reviews 209, 103324. https://doi.org/10.1016/j.earscirev.2020.103324

Woo, J., Magee, C.L., 2022. Relationship between technological improvement and innovation diffusion: an empirical test. Technology Analysis & Strategic Management 34, 390–405. https://doi.org/10.1080/09537325.2021.1901875

Yaïci, W., Longo, M., 2022. Feasibility Investigation of Hydrogen Refuelling Infrastructure for Heavy-Duty Vehicles in Canada. Energies 15, 2848. https://doi.org/10.3390/en15082848

Yip, H.L., Srna, A., Yuen, A.C.Y., Kook, S., Taylor, R.A., Yeoh, G.H., Medwell, P.R., Chan, Q.N., 2019. A Review of Hydrogen Direct Injection for Internal Combustion Engines: Towards Carbon-Free Combustion. Applied Sciences 9, 4842. https://doi.org/10.3390/app9224842

Zalzal, J., Hatzopoulou, M., 2022. Fifteen Years of Community Exposure to Heavy-Duty Emissions: Capturing Disparities over Space and Time. Environ. Sci. Technol. 56, 16621–16632. https://doi.org/10.1021/acs.est.2c04320

# Supplemental Materials

To determine the split between long-haul and short-haul heavy-duty vehicles within Alberta, if we initially assumed that 100% of the vehicles are heavy-duty, HDVs must therefore follow the average VKT as provided by Natural Resources Canada (NRCAN). NRCAN indicates an average VKT value of 95,644 for HD vehicles. However, recognizing that HD vehicles typically average around 120,000 VKT, and about 180% of that in the first year being upwards of 200,000 annual VKT, it is clear there must be a significant short-haul vehicle population to offset this discrepancy.

To accurately bookend the split between short-haul and long-haul HD trucks, we considered the average VKT for battery electric vehicles (BEVs) in the short-haul market, which ranges from 30,000 to 50,000 VKT per year. We then determined that the SH population must be between 15% and 30%, as to not go outside of the reasonable range of VKT as seen in **Fig. S1** below, both for average VKT and VKT in year 1.

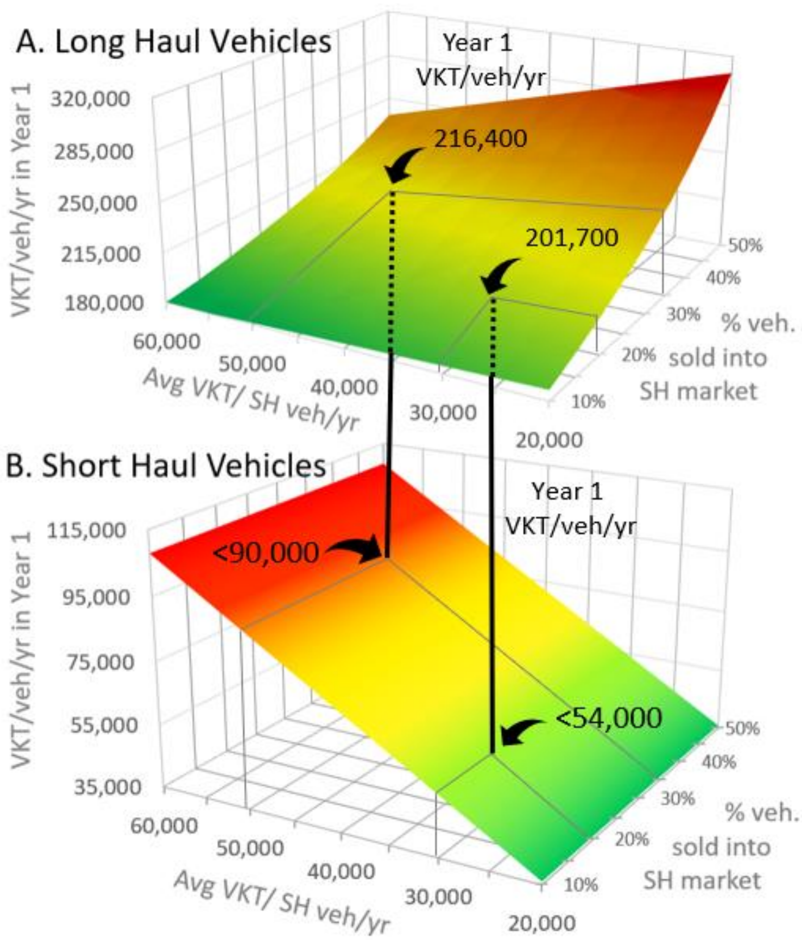



**Fig. S1.** Bookending the Split of Short-Haul and Long-Haul HD Trucks Within Alberta. *Bookends were determined from the range comparison of what % were sold into the SH market, which was only reasonable between 15% and 30% for SH, and the average VKT of which BEVs which was determined to be between 30,000 and 50,000 VKT per year.*