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Zero-emission tractor-trailers in Canada

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Introduction

There is growing interest in deploying electrified drivetrains in heavy-duty freight vehicles for a number of reasons, including climate change, energy diversification, and local air quality. Climate change provides a key overarching motivation for most major national and local governments, and the contribution of trucking activity to greenhouse gas (GHG) emissions helps underscore the imperative to focus not just on cars, but on heavy-duty freight vehicles as well.

As shown in Figure 1, the transportation sector represents about 25% of Canada's CO_2-equivalent (CO_2e) emissions. Of that 25%, heavy-duty trucks make up roughly 35% of transport emissions (rail represents about 3 percentage points of the heavy-duty trucks and rail portion) and 8% of total GHGs in Canada (Environment and Climate Change Canada 2018).

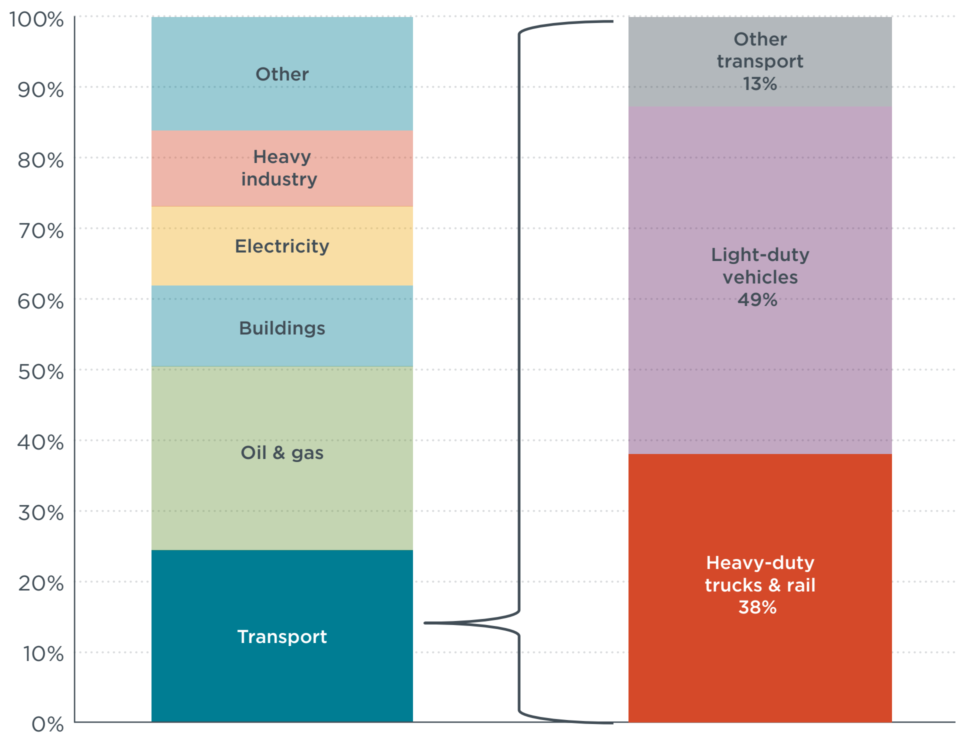

Figure 1. Breakdown of CO_2e emissions in Canada by sector in 2016

Figure 2 summarizes the breakdown of the vehicle population, travel activity, and GHG emissions for the on-road fleet in Canada. Heavy-duty trucks account for a large and growing share of local pollutant and GHG emissions. Despite representing merely 14% of the vehicle stock and 21% of total vehicle kilometers driven, heavy-duty freight trucks accounted for approximately 37% of the life-cycle road vehicle GHG emissions (International Council on Clean Transportation 2019).

In Canada, the majority of goods that are transported by road are borne by heavy-duty combination tractor-trailers. As a result, tractor-trailers account for the largest percentage of vehicle kilometers traveled (VKT) and thus the

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most fuel consumption and emissions from the heavy-duty vehicle sector. Figure 3 illustrates the contribution of tractor trucks to CO_2e emissions from 2015 projected through 2050. Based on business-as-usual vehicle efficiency trends for policies currently in place, the share of fuel use and GHGs from tractor-trailers is projected to grow from 18% in 2015 to 29% in 2050 (International Council on Clean Transportation 2019).

Many governments seek to break down barriers to decarbonize heavy-duty freight trucks by leveraging progress on electric cars. Given the activity and emissions trends introduced above, it is increasingly clear that long-term climate and air-quality goals will require that all major transport modes move toward much lower emissions, including through the broad application of plug-in electric and hydrogen fuel cell technology. Many of these technologies, in greater use in light-duty vehicles, are also being explored for deployment in heavy-duty freight vehicles.

To inform such government activities on zero-emission heavy-duty vehicles, it is important to gain a clearer understanding of the potential viability for the various zero-emission heavy-duty vehicle technologies. In this study, we focus on the following zero-emission technology options, which are all in the very early stages of development and commercialization for Class 7 and 8 trucks: hydrogen fuel cell, battery electric, and overhead catenary electric. The primary objective of this study is to estimate the Canada-specific operations costs and CO_2e emissions for these zero-emission trucks as compared with their diesel and natural gas counterparts. This research builds on an earlier ICCT study (Moultak, Lutsey et al. 2017).

We first review the literature to explore two issues that are of particular significance for the performance of electric trucks in Canada: vehicle weight and cold temperatures. We then assess vehicle-related cost of ownership for diesel, diesel hybrid, natural gas, hydrogen fuel cell, battery electric, and overhead catenary trucks in the 2025–2030 time frame. We then analyze these technologies by their life-cycle greenhouse gas emissions, including upstream fuel cycle emissions. We next analyze the costs and emissions benefits of battery electric trucks compared with conventional diesel for certain high-volume trucking corridors in Canada. Finally, we summarize and discuss the results.

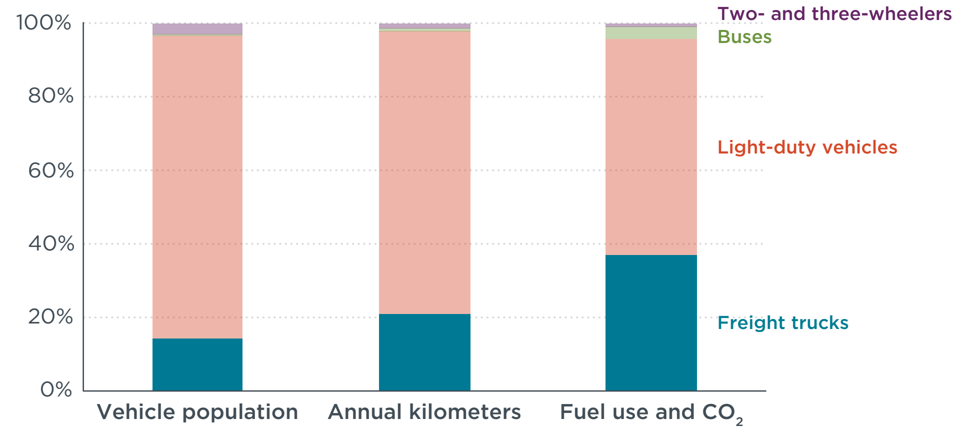

Figure 2. Canada vehicle stock, distance traveled, and life-cycle road transport GHG emissions by vehicle type in 2015

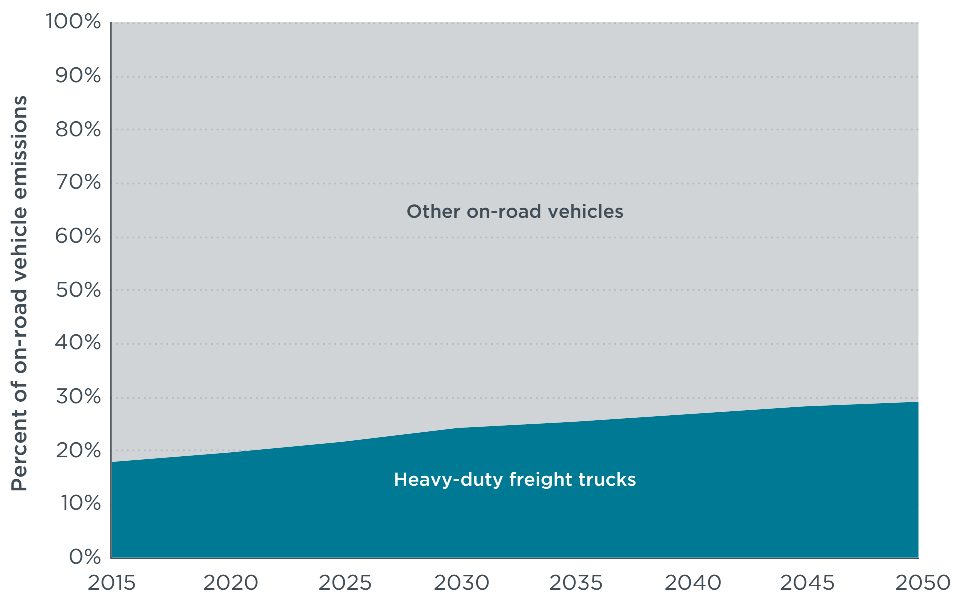

Figure 3. Contribution of tractor-trailers in Canada to total CO_2e emissions from 2015 to 2050

Weight and temperature considerations for battery electric tractor-trailers

While few zero-emission heavy-duty commercial freight vehicles are on the road today, a number of studies over the past five years have considered the feasibility of a variety of technologies and their potential to reduce emissions. A previous ICCT paper summarizes several research studies that examine the technical prospects and fuel use and emission reduction potential of zero-emission propulsion options for medium- and heavy-duty vehicles (Moultak, Lutsey et al. 2017). Those authors also discuss the current state of technology and commercial status for zero-emission options, including battery electric and hydrogen fuel cell, as well as electric trucks that are dynamically charged —via overhead catenary transmission, on-road conductive tracks, or in-road inductive wireless charging.

Of these zero-emission options, battery electric and hydrogen fuel cell trucks are emerging as the early leaders in terms of prototypes and commercialization in the Class 7 and 8 trucking space.[1] In the past year, there have been product launch announcements from startups (e.g., Tesla, Thor, Nikola) and more well-established vehicle and engine manufacturers (e.g., Daimler, Cummins, Toyota). Many of these companies have rolled out prototypes and are in the beginning stages of deploying trucks into real-world service in Canada and the United States. (Nikola Corporation 2016, Claflin 2017, Visnic 2018, Daimler Trucks North America LLC 2019, Tesla 2019, Thor Trucks Inc. 2019).

Financial considerations aside, for zero-emission trucks to reach large-scale deployment, they must be able to meet or exceed the performance, reliability, and durability of diesel trucks.

1 In North America, a Class 7 truck is classified as a vehicle with a maximum weight (including payload) of 26,501 to 33,000 lb and a Class 8 truck as greater than 33,000 lb. Virtually all tractor-trailers are either Class 7 or 8 vehicles, though many other truck and bus types are included in these weight categories (e.g., transit buses, refuse trucks, delivery trucks, cement mixers).

Table 1. Parameters for battery electric tractor-trailer energy demand analysis

Component	Parameter	Value	
Chassis	Total tractor-trailer weight (kg)	36,287	-
	Aerodynamic drag coefficient (-)	0.36	Tesla (2019)
Final drive	Final drive ratio (-)	2.64	Delgado & Lutsey (2015)
Wheel axle	Drive tire coeff. of rolling resistance (C_{RR})	4.5	
	Steer tire C_{RR}	4.3	
	Trailer tire C_{RR}	4	
Accessories	Electrical (kW)	1.35	
Simulated energy demand at the wheels	Kilowatt-hours per kilometer	1.6	This study

In terms of performance, there are two areas that are of particular concern for zero-emission trucks: heavier curb (empty) weights of the vehicles and reduced driving range in cold temperatures. In the following two subsections, we review the literature and use publicly available data to estimate the additional weight and cold-temperature impacts of a battery electric truck. Hydrogen fuel cell trucks are not included in the weight analysis due to limitations in our vehicle simulation software. Regarding temperature, data from several years of fuel cell bus evaluations indicate that the range and performance of fuel cell vehicles is not compromised in cold weather (Eudy and Post 2018).

WEIGHT CONSIDERATIONS OF BATTERY ELECTRIC TRACTOR-TRAILERS

For this analysis, we simulated a generic electric truck in Autonomie using the vehicle input parameters shown in Table 1. Autonomie is a vehicle performance evaluation software platform that was developed by the U.S. Department of Energy's Argonne National Laboratory (UChicago Argonne LLC 2019). With several of the battery electric truck makers claiming their vehicles can perform well at maximum allowable weight, we analyzed the vehicle at 36,287 kg (80,000 lb), which is the weight limit for the combination tractor-trailer in many jurisdictions across North America. Though this analysis is done at 80,000 lb, an important consideration is that while the large majority of tractor-trailers in the United States are subject to an 80,000-lb weight limit, Canada has a much larger percentage of tractor-trailers carrying heavier payloads. In Canada, where tractor-trailers are often heavier than 120,000 lb, zero-emission trucks must operate at these heavy loads if they are going to eventually replace diesels completely.

For the remaining vehicle parameters, we used inputs based on a 2015 study (Delgado and Lutsey 2015) and our best judgment. We ran the vehicle over the highway cruise portion of the Heavy Heavy-Duty Diesel Truck (HHDDT) cycle[2], where speeds hover around 105 km/h (65 mph). The resulting energy demand at the wheels is approximately 1.6 kilowatt-hour per kilometer (kWh/km).

2 The heavy heavy-duty diesel truck (HHDDT) is a chassis dynamometer test that consists of four modes: idle, creep, transient, and cruise. A fifth mode, also known as the high-speed cruise HHDDT65 cycle, represents higher speed freeway operation at 65 mph and combines elements of each of these modes.

With this data point for total energy demand at the wheels, we are able to calculate an estimated weight of the battery pack. Table 2 summarizes the various steps and data used in the calculation. With 1.6 kWh/km needed to power the truck, if we assume a range of 805 km (500 miles) and a usable battery capacity of 80%[3], that results in a battery size of roughly 1,640 kWh. Based on information from existing light-duty electric vehicles and assumed improvements that will be achieved for heavy-duty applications, we estimate a battery pack energy density of 0.2 kWh/kg (EVANNEX 2019). Dividing the battery size (1,643 kWh) by 0.2 kWh/kg gives a total pack weight of about 8,400 kg. We then estimate the weight of the power electronics (i.e., inverter, motors, and gearboxes), again using data from the passenger vehicle segment (Teslarati 2013, Motor Trend 2017, InsideEVs.com 2019). Altogether, we estimate nearly 9,000 kg for the weight of the battery pack and power electronics. Removing the powertrain and fluids from a diesel truck eliminates about 3,000 kg (U.S. Department of Energy: Office of Energy Efficiency and Renewable Energy 2019), so the electric truck in this example would have a net weight increase of about 6,000 kg compared with a conventional vehicle. At roughly 36,300 kg, the maximum payload a diesel truck can haul is about 21,600 kg (assuming roughly 14,700 kg empty weight). Thus, the 6,000 kg of additional weight of the battery electric truck in this example represents a loss of payload of 28%. This is a significant reduction in maximum payload, and fleets that tend to carry heavy loads would have great difficulty in deploying battery electric trucks unless there are significant advances in battery energy density. Even with a 50% improvement in energy density (0.3 kWh/kg), the battery electric truck in this example would have a roughly 3,200-kg loss of payload.

Table 2. Vehicle parameters for battery electric tractor-trailer energy demand analysis

	Parameter	Formula	Value	Source
A	Power demand at the wheels (kWh/km)		1.6	This study
B	Nominal range (km)		805	Tesla (2019)
C	Usable battery capacity		80%	Tesla (2019)
D	Required battery pack size (kWh)	A x B / C	1,643	-
E	Battery pack energy density (kWh/kg)		0.20	EVANNEX (2019) and author's best judgment
F	Battery pack weight (kg)	D / E	8,378	-
G	Motor rated power (kW)		175	Motor Trend (2017)
H	Number of motors needed for semi truck		4	InsideEVs.com (2019)
I	Total rated power (kW)	G x H	700	-
J	Weight of motor, inverter, and gearbox (kg/kW)		0.88	Teslarati (2013)
K	Weight of motor, inverter, and gearbox (kg)	I x J	618	-
L	Total weight of battery and power electronics (kg)	F + K	8,996	-
M	Weight of powertrain and fluids in diesel truck (kg)		3,000	U.S. DOE, EERE (2019)
	NET ADDITIONAL WEIGHT OF BATTERY ELECTRIC TRACTOR-TRAILER (kg)	**L - M**	**5,996**	-

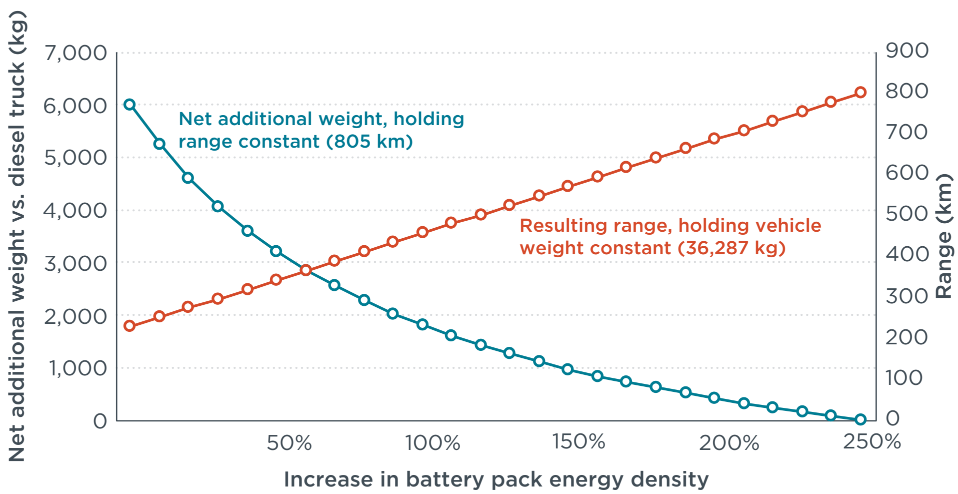

Figure 4. Battery pack density impacts on electric tractor-trailer weight and range

Figure 4 shows the impacts of increasing the energy density of the battery pack. At the left end of the figure, the baseline battery energy density is 0.2 kWh/kg, which increases in 10 percentage point increments moving to the right. The blue curve is the resulting additional net weight of the electric truck, assuming a constant range of 805 km. For the electric truck in this example to be at maximum weight

3 According to the CALSTART study on truck electrification (2014), fleets typically apply a safety factor to the advertised maximum range limit. We use the same 80% value as in the CALSTART analysis.

(36,287 kg) and successfully complete 805 km of driving without any weight penalties versus a conventional diesel, the battery energy density would need to be 0.69 kWh/kg. The orange curve shows the resulting vehicle range if we hold the total truck weight constant at 36,287 kg. As shown, the baseline energy density of 0.2 kWh/kg results in a range of about 230 km, and this value grows linearly as battery pack energy density increases.

Continued improvements in battery technology are expected, and battery pack energy densities in vehicle applications are projected to double over the next 5 to 7 years (Cano, Banham et al. 2018). Heavy-duty electric vehicle manufacturers will certainly depend on these advancements in battery technology to be competitive with diesel and other fossil fuel-powered trucks.

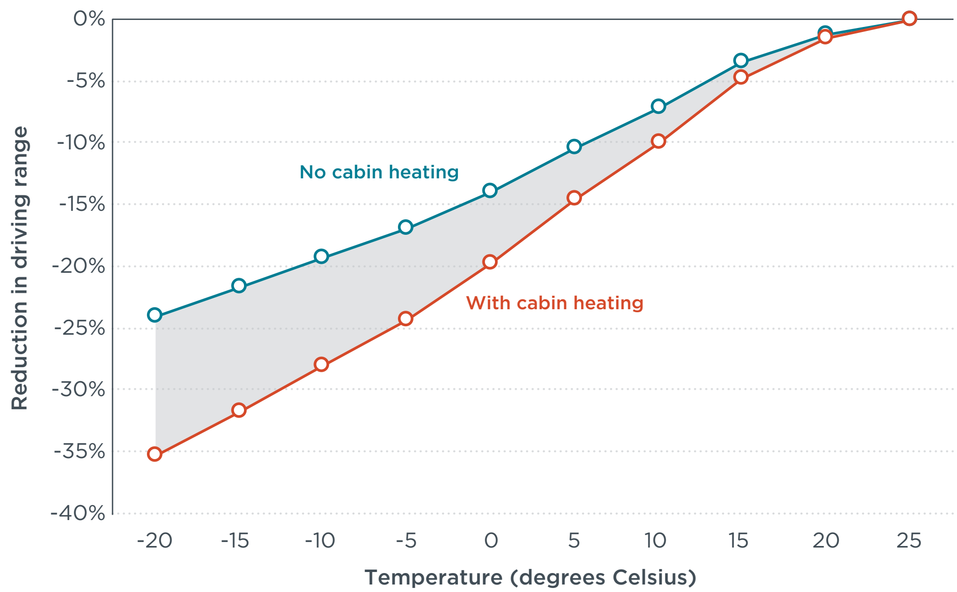

Figure 5. Estimated loss in driving range of battery electric tractor-trailer as a function of temperature

TEMPERATURE IMPACTS ON BATTERY ELECTRIC TRACTOR-TRAILER PERFORMANCE

In additional to the weight concerns, reduced battery performance in cold temperatures is an important barrier to large-scale commercialization of zero-emission trucks, especially in Canada. There are several studies that analyze the effects of cold temperatures on the battery performance and driving range of light-duty electric cars (Christenson, Loiselle-Lapointe et al. 2014, Loiselle-Lapointe, Conde et al. 2015, Taggart 2017, Loiselle-Lapointe, Pedroso et al. 2018), and one study examines this issue for commercial trucks (CalStart 2014). According to the literature, colder temperatures affect battery electric vehicle performance in two ways: 1) increase in auxiliary power consumption for cabin heating and window defrosting, and 2) battery chemistry is less efficient in severe temperatures (cold or hot).

To estimate the reduction in battery electric truck range due to increased auxiliary loads, we used the same vehicle modeling parameters as in the previous section, though we assumed a vehicle test weight of 31,900 kg. This test weight was selected because it is roughly the weight under which Class 8 tractor-trailers are evaluated in the GHG regulation for on-road commercial vehicles in Canada and the United States. For the increased power demand of a cabin heater, we assumed an additional 5 kW of constant load (CalStart 2014). With this additional accessory load, energy consumption over the HHDDT 65 mph cycle and HHDDT transient cycle increased by 4% and 13%, respectively. The increase in energy consumption is larger over the transient cycle because accessory loads make up a larger percentage of overall losses in cycles with lower speeds and more acceleration and deceleration events (Delgado and Lutsey 2015).

We did not estimate the reduction in range due to battery temperature effects in Autonomie, but rather we adapted the data provided in Figure 3 in Taggart (2017), which analyzed electric vehicle performance from approximately 2.5 million trips. Compared with tractor-trailers, light-duty vehicles typically have much shorter trips and therefore spend a higher percentage of time with the battery operating at colder temperatures, and range impacts are more significant. To account for the fact that cold temperature impacts on driving range are more significant for shorter trips, Taggart analyzes driving range as a function of temperature for different trip distances. Figure 3 in that study estimates the relationship between ambient temperature and reduction in driving range for trips of three different ranges including 80-plus mile trips, the longest trips within the dataset. We translated the Taggart data from 80-plus mile trips into percentage reduction in driving range, which is shown in the blue curve in Figure 5. The "No cabin heating" scenario represents the reduction in range due solely to battery temperature effects.

To estimate the loss in driving range due to increased cabin heating demands, we assumed an additional heating power demand of 5 kW at -20°C and a linear reduction of this accessory load down to zero at 25°C, where we assume the battery pack operates at maximum efficiency. The orange curve in Figure 5 represents the decrease in range due to both battery temperature effects and additional cabin heating over the HHDDT transient cycle. Because the losses due to additional accessory loads are larger in the transient cycle than in the highway cruise cycle, the orange curve represents our estimated upper bound for the total losses in driving range for battery electric trucks as a function of temperature.

As battery electric tractor-trailers are increasingly deployed as replacements for diesel (and other fossil-fuel-powered) vehicles, trucking fleets are going to expect that the performance is roughly comparable to their conventional counterparts. As discussed in this section, the battery weight concerns and cold temperature impacts are considerable barriers to the accelerated deployment of battery electric trucks across the full spectrum of trucking applications.

Technology cost analysis

To assess zero-emission vehicle technology costs, in the two subsections below we develop a cost of ownership evaluation of the various vehicle technology alternatives.

VEHICLE COST OF OWNERSHIP

To gain an understanding of the viability of various zero-emission heavy-duty technologies for long-haul heavy-duty tractor-trailer applications, we analyzed the technologies under a vehicle-related cost of ownership framework. We base the analysis on the research and available data on vehicle technology costs, efficiency, and emissions from Moultak et al. (2017). We report on results for 2015 through 2030 to show our best estimates of the progression of the costs over time.

The objective of the cost analysis is to illustrate the cost differences of various tractor-trailer technologies over different periods of time. The analysis includes capital costs (tractor-trailer purchase price), maintenance costs, and fuel costs experienced by the owner over the vehicle lifetime. The fuels and technologies considered in the analysis are diesel, diesel hybrid, compressed natural gas, liquefied natural gas, overhead catenary line electric, and hydrogen fuel cells. All costs in the analysis are in 2018 Canadian dollars. The analysis is constrained to vehicle and fuel costs. Motor vehicle taxes, insurance costs, driver wages, tolls, and road fees are excluded. We make a series of assumptions on average annual vehicle use, efficiency technology, cost, and fuel cost to develop bottom-up cost models for the various tractor-trailer technologies. Vehicle technology and maintenance costs are taken directly from our 2017 study (Moultak, Lutsey et al. 2017), so the focus here will be on highlighting the Canada-specific fuel cost inputs in the analysis.

The data and methods used to estimate historical and projected end user fuel costs for diesel, natural gas, hydrogen (natural gas-sourced and renewable-sourced), and electricity are summarized in the bottom portion of Table 3.

Figure 6 shows the vehicle-related cost of ownership for 2015 through 2030.

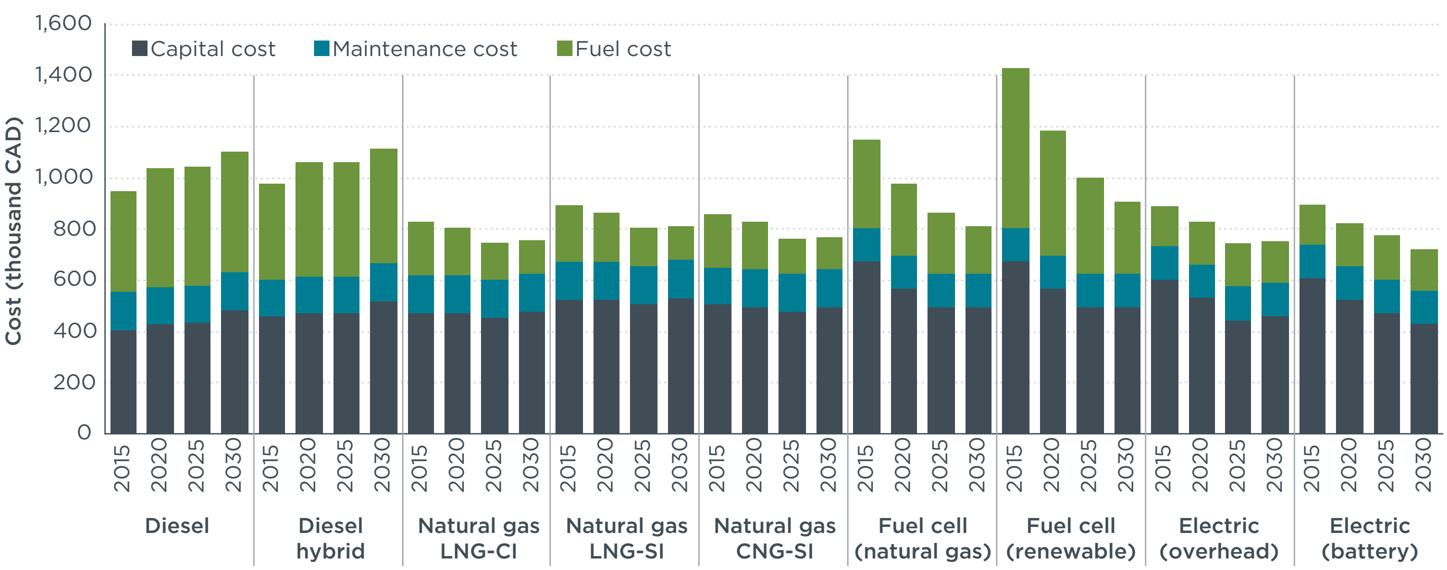

Figure 6. Cost of ownership for each tractor-trailer technology for a vehicle purchased in 2015–2030 broken down by capital cost, maintenance cost, and fuel cost, excluding infrastructure costs. No battery replacements are assumed for either type of electric truck.

Table 3. Canada-specific data inputs

Parameter	Value and/or method	Source
U.S. dollars (2015) to Canadian dollars (2018)	(1) Convert USD 2015 to 2018 (annual average) (2) For 2018 annual average, convert USD to CAD	(Bureau of Labor Statistics 2019, USForex Inc. 2019))
Average annual vehicle kilometers traveled	90,000 km	(Cheminfo Services Inc. and the North American Council for Freight Efficiency 2017))
Carbon intensity of fuels		
Diesel	94.2 gCO_2e/MJ	((S&T) Squared Consultants Inc. 2019))
Hydrogen (gaseous) from natural gas	105.7 gCO_2e/MJ	
Compressed natural gas	64.4 gCO_2e/MJ	
Liquefied natural gas	68.9 gCO_2e/MJ	(California Air Resources Board 2018, (S&T) Squared Consultants Inc. 2019))
Electricity grid mix and CO_2e emissions, and carbon intensity 1990–2016. National average and by province and territory.	Carbon intensity calculated by dividing total CO_2e emissions by total generation capacity	(Environment and Climate Change Canada 2018))
Electricity grid mix and CO_2e emissions, and carbon intensity 2017–2040. National average and by province and territory.	Using baseline (2016) electricity grid mix from Environment and Climate Change Canada, 2017–2040 values are estimated using National Energy Board projections.	(National Energy Board 2017, Environment and Climate Change Canada 2018))
End user prices for fuels		
Diesel	Historical: 2015–2018	(Natural Resources Canada 2019))
	Growth rate derived from IEA projections out to 2040	(International Energy Agency 2017))
Hydrogen (gaseous) from natural gas	(1) Price from the STEPS study for liquid hydrogen from natural gas is adjusted based on the average price difference between natural gas in the United States and Canada and the estimated portion of hydrogen fuel costs due to natural gas feedstock costs. (2) The price of gaseous hydrogen is estimated based on ratio of the price of gaseous to liquid natural gas.	(National Research Council and National Academy of Engineering 2004, Fulton and Miller 2015, U.S. Department of Energy: Office of Energy Efficiency and Renewable Energy 2016, BP 2018))
Hydrogen (gaseous) from renewables	(1) The price from the STEPS study for liquid hydrogen from renewables is adjusted based on the average price difference between electricity in the U.S. and Canada and the estimated portion of hydrogen fuel costs due to electricity costs. (2) The price of gaseous hydrogen is estimated based on ratio of the price of gaseous to liquid natural gas.	
Natural gas	Historical and projected values for Canada based on a ratio of the difference between U.S. and Canadian price data from BP. The difference in price between Canada and the United States is assumed to be constant over the study period. U.S. price data for 2015– 2040 comes from the U.S. EIA.	(U.S. Energy Information Administration 2017, BP 2018))
Electricity: national average and major cities	Historical: 2015– 2018	(Hydro-Québec 2018))
	Growth rate derived from U.S. EIA projections out to 2050	(U.S. Energy Information Administration 2017))

The graphs show the breakdown of the tractor-trailer capital cost, maintenance cost, and fuel cost over 10 years of operation. The cost analysis excludes infrastructure cost for overhead catenary technologies. By analyzing the 10-year operating cycle, we intend to cover at least the first phase of the tractor life while it is in long-haul operation. With uncertainties about total electricity throughput, charging-discharging cycles, and any degradation over time for catenary and in-road charging electric tractors, we do not include battery replacements. The results are summarized for the various vehicle technologies as compared with conventional diesel (which increases in efficiency over time), diesel hybrid (which retains an efficiency advantage over conventional diesel), and three natural gas technologies: liquefied compression ignition (LNG-CI), liquefied spark ignition (LNG-SI), and compressed spark ignition(CNG-SI). Two fuel cell technology pathways are shown: the first for natural gas-derived hydrogen and the second for renewable source-derived hydrogen.

The figure shows how conventional diesel vehicle costs increase incrementally, but are relatively consistent into future years, as compared with the alternative fuel technologies. Essentially all the other technologies see reduced cost of ownership over time, primarily because their capital technology costs drop from 2015 through 2030. Natural gas trucks consistently yield the lowest cost of ownership.

The zero-emission vehicle technologies show the greatest cost reductions from 2015 to 2030. Fuel cell technology shows the largest reduction in cost over time, due to the expected drops in fuel cell costs and hydrogen costs. Excluding infrastructure costs, the two electric vehicle scenarios, catenary and battery electric, ultimately arrive at among the lowest total vehicle cost in the 2025–2030 time frame, similar to natural gas. As compared with diesel vehicles in the 2030 time frame, overhead catenary and battery electric result in roughly 30% to 35% lower costs, and hydrogen fuel cells result in 15% to 25% lower costs to own, operate, and fuel. The projected costs for electric tractor-trailers would bring their upfront costs in line with conventional diesel trailers in the 2025–2030 time frame.

PROVINCE AND TERRITORY-SPECIFIC COST RESULTS FOR BATTERY ELECTRIC TRACTOR-TRAILERS

We used electricity price data for commercial customers in several cities in Canada to estimate average prices at the provincial and territorial level, and Figure 7 shows the results. In the figure, each of the 10 provinces and three territories has two bars: the solid bar represents the difference in electricity prices versus the national average, and the dashed bar shows the difference in total costs, factoring in capital and maintenance costs. Because fuel costs are a subset of the total costs, the difference in fuel costs (solid columns) for each province is larger in absolute value than the difference in total costs. Provinces with red columns—Alberta, British Columbia (BC), Manitoba, Newfoundland and Labrador, and

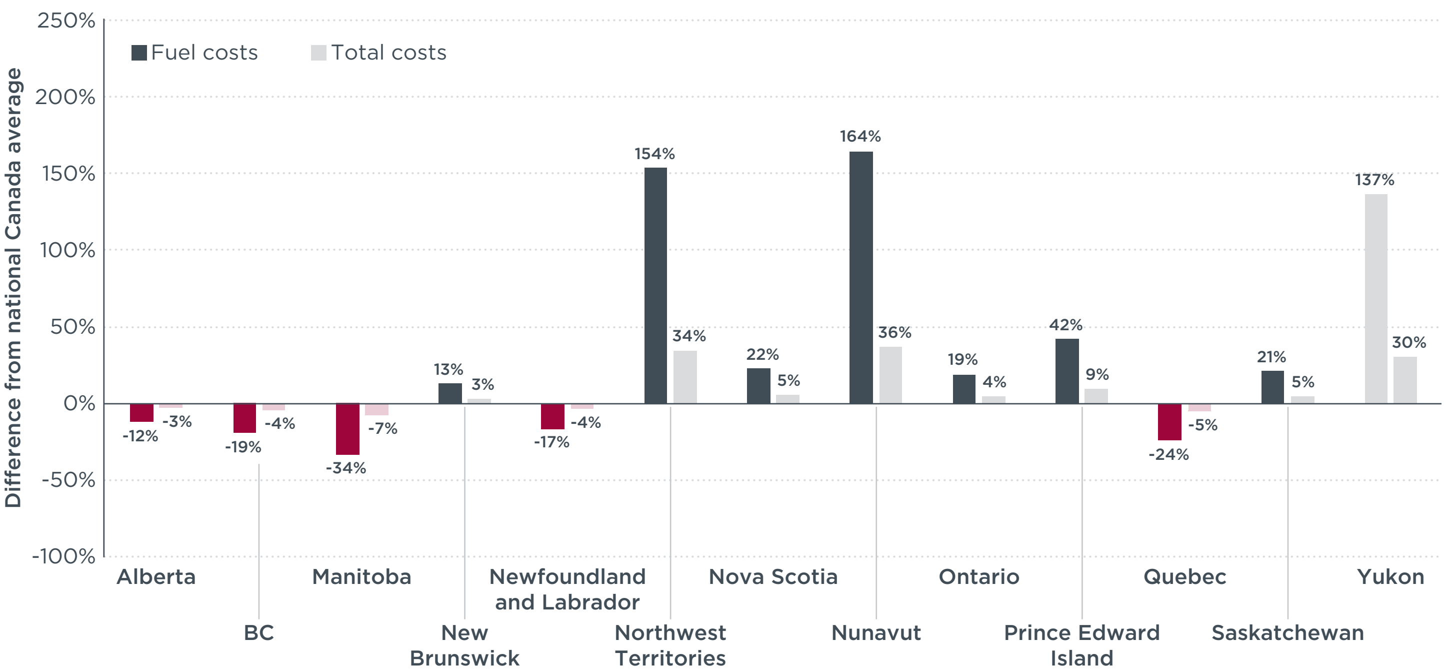

Figure 7. Battery electric tractor-trailers: Factor difference in electricity costs and vehicle cost of ownership from the Canada average

Quebec—have electricity costs lower than the national average, and the opposite is true for the remaining eight provinces. The three northern-most territories—the Northwest Territories, Nunavut, and Yukon—have the highest electricity costs, at roughly 2.5 times the national average. These higher electricity costs translate to between 30% and 36% increased cost of ownership for an electric truck versus the national average. For the remaining 10 provinces, the cost of ownership for an electric truck is within plus/minus 10% of the Canada average.

Analysis of emissions impacts

PER-VEHICLE LIFETIME GREENHOUSE GAS EMISSIONS

To gain an understanding of the emissions impacts of the various tractor-trailer technologies, we analyze the life-cycle GHG emissions for each technology for a truck purchased from 2015 to 2030. In addition to the assumptions used above in the cost of ownership analysis, we include the upstream fuel cycle emissions impacts

Table 4. Fuel carbon intensities (gCO_2e/MJ) for 2015 and 2030 and the percentage reduction in emissions from 2015 to 2030

Fuel	Fuel carbon intensity (gCO_2e/MJ)		Greenhouse gas emission reductions in 2030[a]
	2015	2030	
Diesel	94	94	-
Compressed natural gas	64	64	-
Liquefied natural gas	69	69	-
Hydrogen	106	64	-40%
Electricity	42	21	-50%

[a] Greenhouse gas emission reductions include on-vehicle efficiency improvement (i.e., relative megajoule (MJ) per kilometer)

associated with the production of the various fuel. The data and methods we used to estimate fuel carbon intensities were summarized in Table 3.

Table 4 shows the assumed fuel carbon intensities that we apply to our life-cycle analysis. Carbon intensities for diesel and natural gas are assumed to remain constant from 2015 through 2030, while the carbon intensity of hydrogen is expected to decrease significantly as hydrogen transitions from being produced mainly from fossil fuels through steam-methane reformation to being produced from renewable energy sources. For hydrogen's carbon intensity, we apply a 5% annual reduction to assume that progressive policy is in place to ensure that fuel supply is increasingly low-carbon. The carbon intensity of electricity for 2015 and 2016 is based on the National Inventory Report, and projections are based on the data provided in Canada's Energy Future report (National Energy Board 2017, Environment and Climate Change Canada 2018). We note that there are certain provinces (e.g., BC, Manitoba, and Québec), where the electricity carbon intensity is already near zero, due to electricity generation predominantly coming from renewable energy sources—namely hydro. In Ontario, hydro and nuclear together account for nearly 80% of electricity generation,

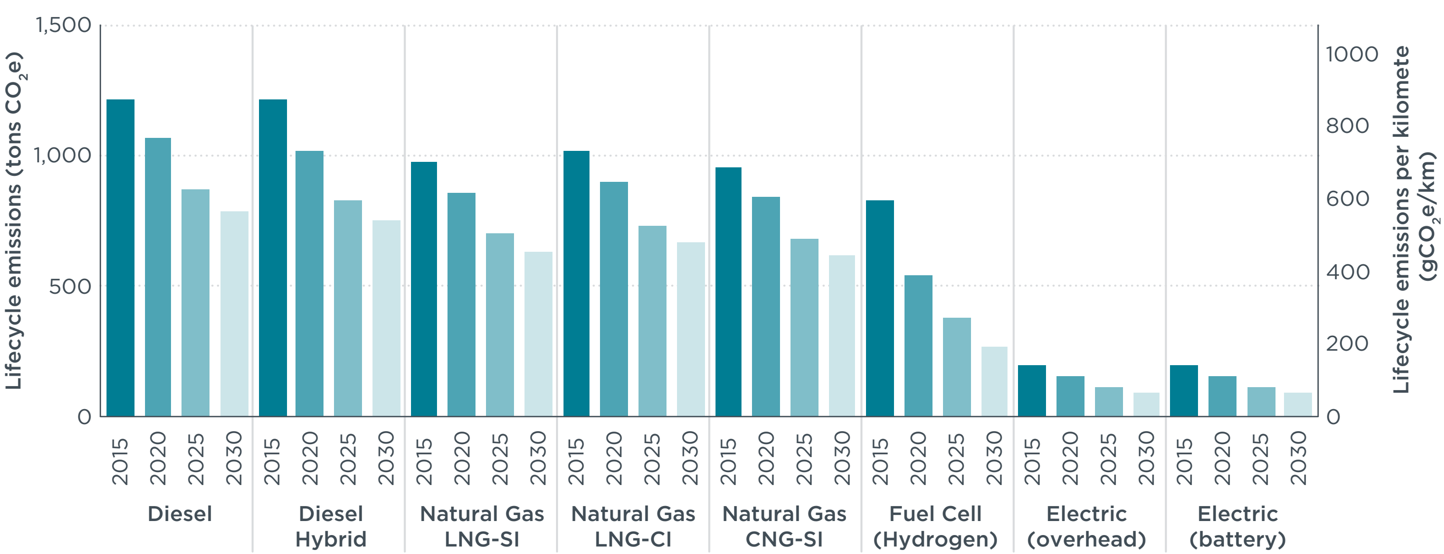

Figure 8. Life-cycle CO_2 emissions over vehicle lifetime (left axis) and per kilometer (right axis) by vehicle technology type

which also leads to a relatively low overall carbon intensity. In such cases, electric trucks offer a more than 95% reduction in carbon emissions versus conventional diesel vehicles.

The total life-cycle wheel-to-well GHG emissions in carbon dioxide equivalents (CO_2e) for each long-haul heavy-duty freight truck technology purchased from 2015 through 2030 are shown in Figure 8.

Major emission differences across the technologies and over time are apparent from the figure. The electric heavy-duty trucks have by far the lowest lifetime emissions. The two electric truck technologies have 84%, 86%, 87%, and 88% lower lifetime CO_2e emissions than conventional diesel vehicles in 2015, 2020, 2025, and 2030, respectively. In those four years, hydrogen fuel cell vehicles have 32%, 53%, 62%, and 72% lower emissions than diesel vehicles. The natural gas technologies have emission levels that are roughly 15% to 20% lower than diesel over the study period. As shown, there is the potential for major reductions in all the vehicle technology types in the 2025–2030 time frame. In the case of the diesel and natural gas technologies, the emission reductions are driven by efficiency technology on the vehicle. On the electric and fuel cell technologies, the emission reductions are driven primarily by the reduced fuel carbon intensity. The diesel tractor-trailer is shown with greatly reduced carbon intensity, with a 35% reduction from 2015 to 2030. The fuel cell technology sees reduced carbon emissions from 2015 to 2030 by 73%. The catenary and battery electric vehicle technology both show a reduction of 54% by 2030.

Table 5. Fuel carbon intensities (gCO_2e/MJ) for 2015 and 2030 in Canada and the United States and the percentage difference

Fuel	2015			2030		
	Canada	United States	Difference	Canada	United States	Difference
Diesel	94	102	-8%	94	102	-8%
Compressed natural gas	64	81	-21%	64	81	-21%
Liquefied natural gas	69	86	-20%	69	86	-20%
Hydrogen	106	151	-30%	49	70	-30%
Electricity	42	144	-71%	21	49	-57%

PROVINCE- AND TERRITORY-SPECIFIC EMISSIONS RESULTS FOR BATTERY ELECTRIC TRACTOR-TRAILERS

We used electricity feedstock mix data from the National Energy Board to estimate electric truck life-cycle CO_2e emissions at the provincial level, and Figure 9 shows the results. The five provinces with near-zero emissions —BC, Manitoba, Newfoundland and Labrador, Prince Edward Island, and Quebec—get virtually all electricity from hydro power. Ontario's grid is also relatively clean, as it derives roughly 80% of its electricity from hydro and nuclear power. The remaining provinces and territories have a higher percentage of their electricity coming from fossil sources, though carbon intensities are projected to drop 15% to 45% between 2015 and 2030.

Using the region-specific carbon intensities for electricity, we performed route-specific analyses for five high-volume trucking corridors

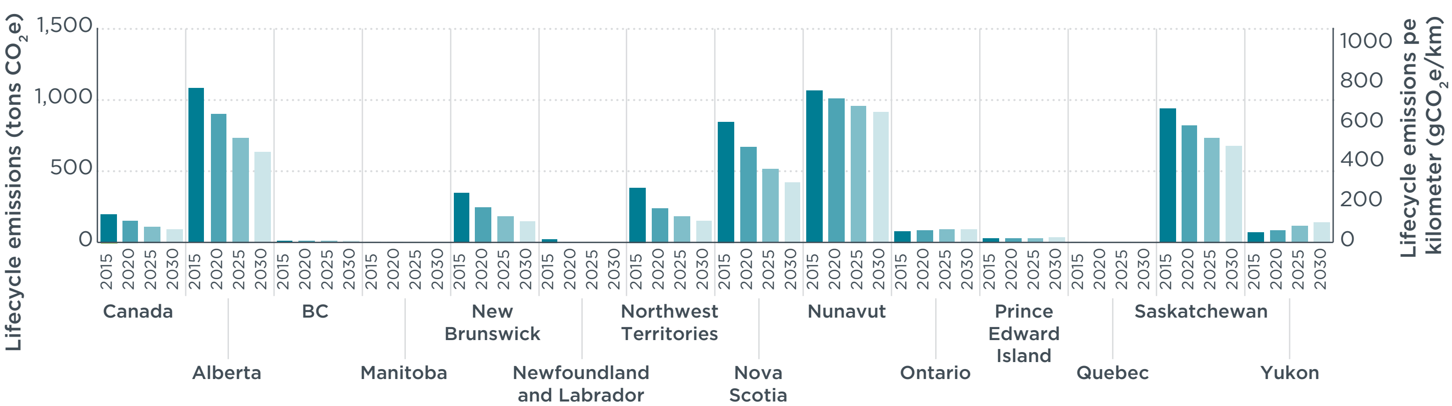

Figure 9. Battery electric tractor-trailers: Province- and territory-specific life-cycle CO_2 emissions over vehicle lifetime (left axis) and per kilometer (right axis)

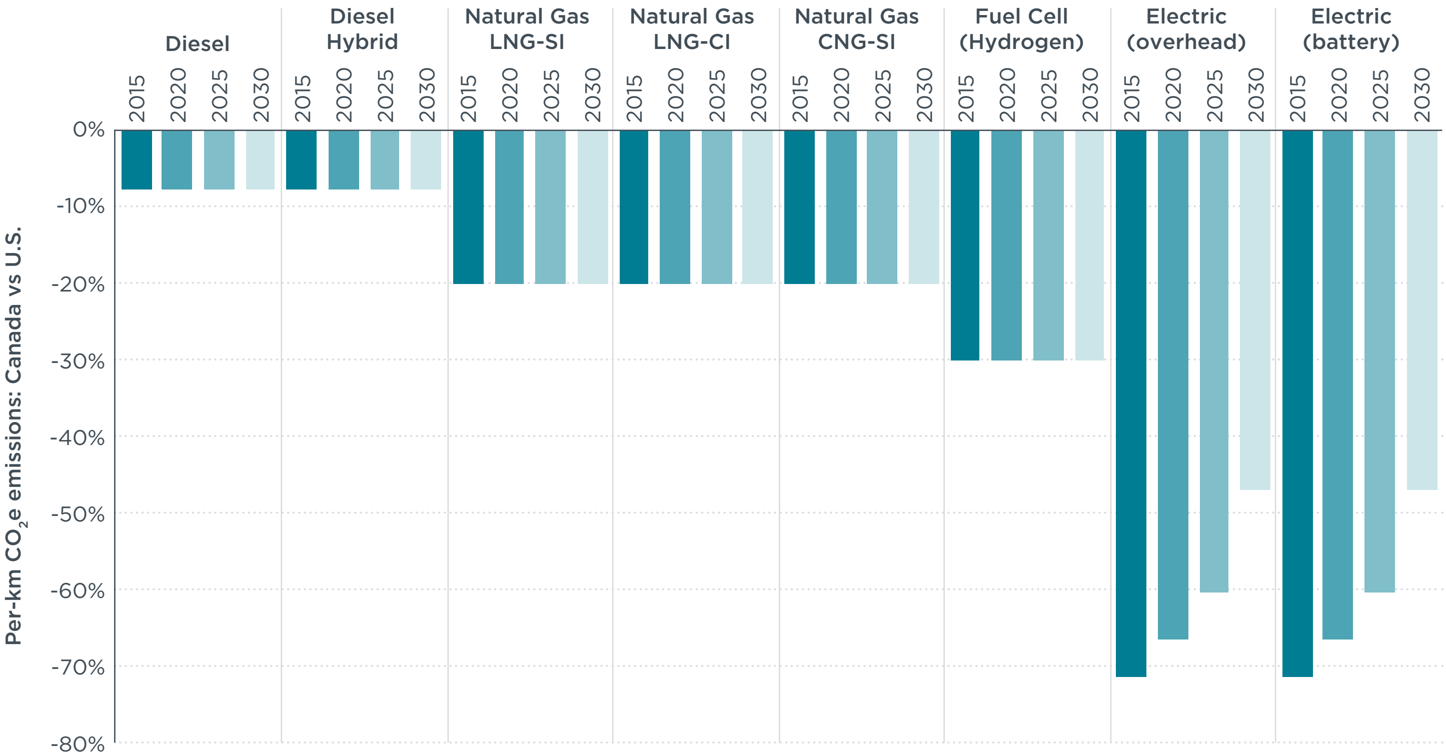

Figure 10. Difference between Canada and the United States in per-km CO_2e emissions for each vehicle technology type

in Canada. These analyses are summarized in the Annex.

DIFFERENCES IN PER-VEHICLE EMISSIONS BETWEEN CANADA AND THE UNITED STATES

As compared with the U.S. results from the Moultak et al. (2017) study, per-km CO_2e emissions for Canada are lower for each fuel and technology option, as shown in Figure 10. For the diesel, natural gas, and hydrogen trucks, the differences in emissions are based solely on the variance in the carbon intensity values in the Low Carbon Fuel Standard (used for the U.S. analysis) and GHGenius (used for this Canada analysis), as summarized in Table 5. The differences in GHG emissions for the catenary and battery electric trucks are significant, with trucks in Canada responsible for over 70% fewer emissions than in the United States. This is due to the fact that Canada's electrical grid is dominated by hydro power (roughly 60% of electricity produced), while coal is the leading feedstock in the United States. Out to 2030, as the U.S. grid is assumed to transition to a higher percentage of renewables, Canada's advantage on electric vehicle emissions decreases, though by 2030 per-km carbon emissions are still nearly 50% lower in Canada.

Findings and conclusions

Decarbonizing heavy-duty vehicle activity by transitioning to zero-emission vehicle technologies, including electricity and hydrogen technologies, presents an immense challenge. Yet there are many promising technologies that have been demonstrated and announced that prove the technical viability and suggest how these technologies could eventually be deployed on a large scale. Mass deployment of zero-emission vehicles can enable greater impact on reducing emissions and energy use, while helping to enable more renewable energy use. The ongoing zero-emission truck projects around the world in 2017 inform where the sector can go if motivated governments and companies act to deploy the technology from 2020 on.

Table 6 summarizes the key data sources and assumptions, methodological shortcomings, and findings for the various elements of this study,

Table 6. Summary of key data sources and assumptions, methodological shortcomings, and findings in the study

	Key data sources and assumptions	Primary shortcomings in the methodology	Findings
Battery electric tractor-trailers: additional weight vs. diesels	• Battery pack energy densities for electric trucks in the 2020 time frame are 0.2 kWh/kg, or ~ 25% to 50% improvement compared with packs in available light-duty vehicles • Vehicle simulation tool: Autonomie, Version 16	• Energy demand assumptions are based on only one drive cycle (HHDDT 65 mph cruise) • Battery pack energy density data and kW/kg assumptions for the weight of power electronics come solely from the light-duty vehicle sector • Road load (i.e., aerodynamic and rolling resistance drag) assumptions are based on unverified manufacturer data and our best judgment	• For an 805-km (500 mile) range and at 36 tonnes (80,000 lb) test weight, a battery electric truck with our modeling parameters weighs ~ 6,000 kg more than a diesel (28% loss in available payload capacity) • Assuming no additional weight vs. a diesel, this battery electric truck has ~ 230-km range • Significant advances in battery pack energy density are needed for battery electric trucks to more effectively compete with diesels
Battery electric tractor-trailers: cold temperature impacts on driving range	• Temperature effects on the battery packs of tractor trucks will be comparable to the light-duty sector; based on Figure 3 in Taggart (2017) • Cabin heating poses a maximum additional load of 5 kW • 31,900-kg test weight • Evaluation from -20° to 25° C	• Lack of literature regarding temperature impacts as a function of battery pack size • Virtually all available literature is centered around light-duty vehicles	• From battery temperature effects, driving range is reduced by ~ 25% at -20° C • Losses due to additional cabin heating result in greater percentage increase in fuel consumption for transient cycle as compared with highway cruise cycle • At -20° C, the estimated upper bound for the total loss in driving range is 35%
Zero-emission vs. fossil fuel-powered tractor-trailers: vehicle-related cost of ownership	• Capital and maintenance costs for all vehicle types are identical to the values used in Moultak et al. (2017) • Canada-specific fuel costs were available for diesel, natural gas, and electricity • We assume that over the entire study period (2015 to 2030), zero-emission trucks are comparable on performance, reliability, and durability • Infrastructure costs for diesel, natural gas, hydrogen, and electricity refueling are not taken into account • We assume no battery replacements over the 10-year life of the battery electric truck	• Changes in fuel prices over time are an exogenous input and are not linked to overall demand for the fuel in the transportation sector • Natural gas prices are indexed to the United States and based on an average difference in natural gas prices between Canada and the United States since 1990 • Changes in prices over time for diesel, natural gas, and electricity are based on projections for the United States	• Natural gas trucks are the lowest TCO option over the entire study period • Due to relatively low-cost electricity, electric trucks are lower than diesels on TCO over the entire study period (~ 5% lower in 2015, growing to over 30% lower by 2030) • Hydrogen fuel cell trucks (renewable H2) have the largest TCO reduction between 2015 and 2030 (nearly 40%) • In 2030, electric trucks have lower TCO than fuel cell trucks by 7% to 20%
Zero-emission vs. fossil fuel-powered tractor-trailers: CO_2e emissions	• GHGenius data (Canada-specific) is used for the carbon intensity of all fuels except electricity • Carbon intensities of diesel and natural gas are assumed to be constant over time, whereas hydrogen and electricity values decrease by 40% and 50%, respectively • Electricity carbon intensity is based on grid mix and emissions data from the National Inventory Report (historical) and the National Energy Board (projections)	• More analysis is needed to better understand the differences in fuel carbon intensity factors in GHGenius (this study) vs. California's Low Carbon Fuel Standard (Moultak et al., 2017 study) • Life-cycle emissions estimates do not take into account emissions associated with vehicle production or end-of-life disposal	• Reduced emissions vs. diesels → electric trucks (~ 85% to 90%); hydrogen fuel cell (~ 30 to 70%) • Provinces with a large percentage of hydro-sourced electricity yield battery electric trucks with nearly zero emissions • Electric trucks in Canada have ~ 70% fewer emissions than those in the United States due to Canada's large reliance on carbon-free hydro power (and to a smaller extent, nuclear power, which is also relatively low carbon, after taking power plant construction emissions into account)
Route-specific costs and CO_2e for battery electric vs. diesel tractor-trailers (Appendix)	• City-specific diesel prices and province-specific electricity prices are used in the analysis • Trucks are assumed to fuel up in only the origin city	• City-specific electricity costs were not utilized • Grade and estimated vehicle speed data are not factored into the assumed energy consumption rates	• Overall costs are between 15% and 30% lower for the electric trucks vs. the diesel • Emissions are nearly eliminated (92% to 99% reduction)

including the route-specific analyses, which are summarized in the Appendix.

Zero-emission trucks offer the prospect of lower climate emissions, no tailpipe pollutant emissions, lower fueling cost, greater renewable energy use, and higher on-vehicle energy efficiency. The zero-emission vehicle technologies do, however, present considerable challenges. They have a combination of near- and long-term barriers, issues, and questions that will have to be addressed before they can become widespread replacements for conventional trucks and tractor-trailers that are typically diesel-fueled. These challenges are somewhat different for the three zero-emission vehicle technologies. As a result, the three technologies have different truck segments for which they offer the most promise for widespread commercialization, based on our assessment in 2017 (Moultak, Lutsey et al. 2017). We emphasize the high uncertainty in how these technologies could evolve over the long term for 2030 and beyond. With sustained government and private industry investment, each of these electric-drive technologies has the potential to overcome the various barriers faster than the others. Considering the vast scale of the problem of decarbonizing freight transport, it appears likely that many of the battery and fuel cell technologies will need to grow in parallel to meet medium- and long-distance freight demands as soon as they prove themselves.

Appendix

TOTAL COSTS AND CO_2E RESULTS FOR HIGH-VOLUME TRUCKING CORRIDORS IN CANADA

In the main body of the paper, we describe the vehicle-related cost of ownership and emissions analyses for the fuel and technology options that were included in this study. We also present province- and territory-specific results for the battery electric trucks.

In this appendix, we perform route-specific comparisons for battery electric versus diesel trucks for five high-volume trucking corridors in Canada. For each of the five routes (Toronto to Montreal; Montreal to Quebec City; Toronto to London, ON; Vancouver to Seattle; and Hamilton to Woodstock, ON), we assume that both the diesel and battery electric trucks are fully fueled in the origin city and complete the route without refueling along the route. Thus, the battery electric trucks have upstream emissions associated with the carbon intensity of the electricity in the province of origin. We do not have the required data granularity to estimate electricity carbon intensity at the city level, so the battery electric trucks leaving Toronto and Hamilton are assumed to have identical CO_2e-per-km emissions based on the average electricity carbon intensity in Ontario. The Montreal-to-Quebec City and Vancouver-to-Seattle trips use Quebec- and British Columbia-based carbon intensities, respectively. Finally, we do not take grade into account, and the analysis is set in the year 2020.

For each route, Figures 11 through 15 show the input assumptions for trip length and fuel costs, as well as the TCO and emissions results in terms of percentage reduction versus the diesel truck. The geographic boundary maps for the provinces were created in Mapchart.net (Mapchart.net 2019).

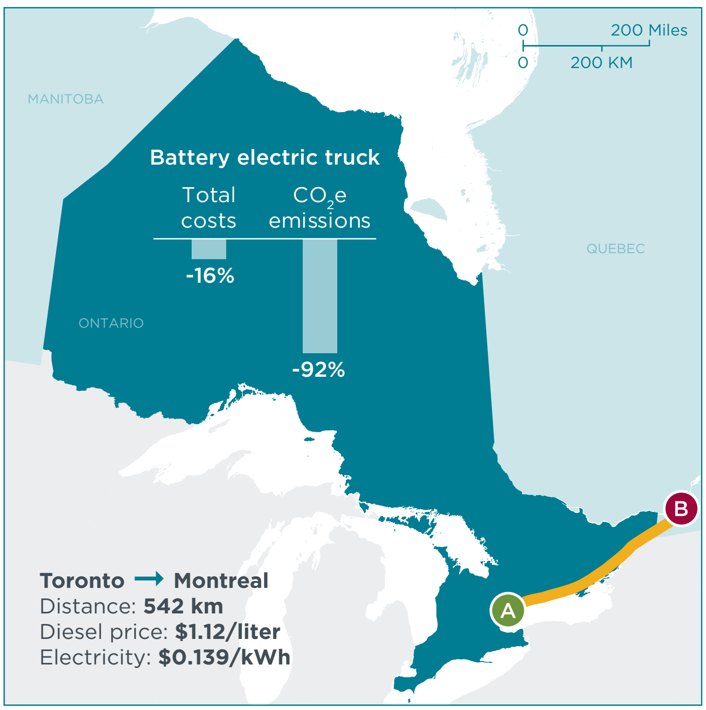

Figure 11. Difference between battery electric and diesel trucks in costs and CO_2e emissions for the Toronto-to-Montreal corridor

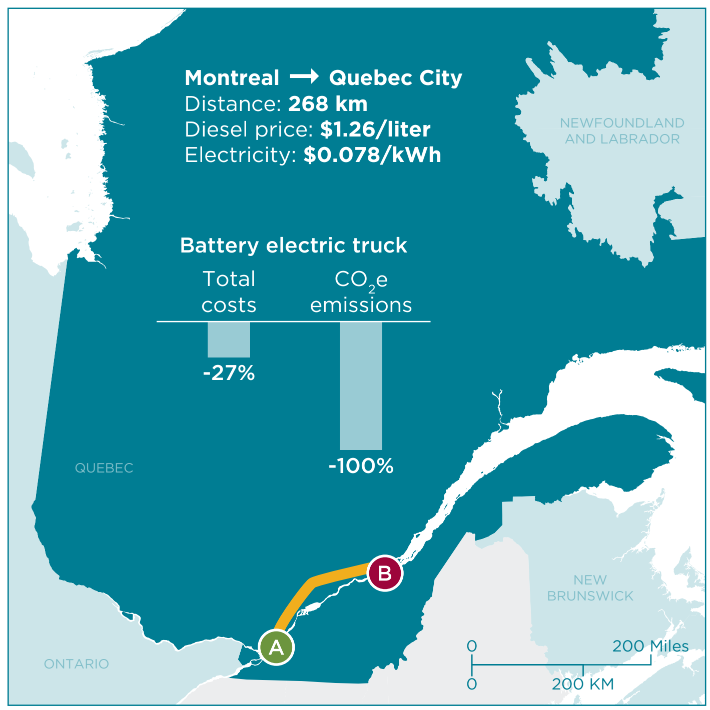

Figure 12. Difference between battery electric and diesel trucks in costs and CO_2e emissions for the Montreal-to-Quebec City corridor

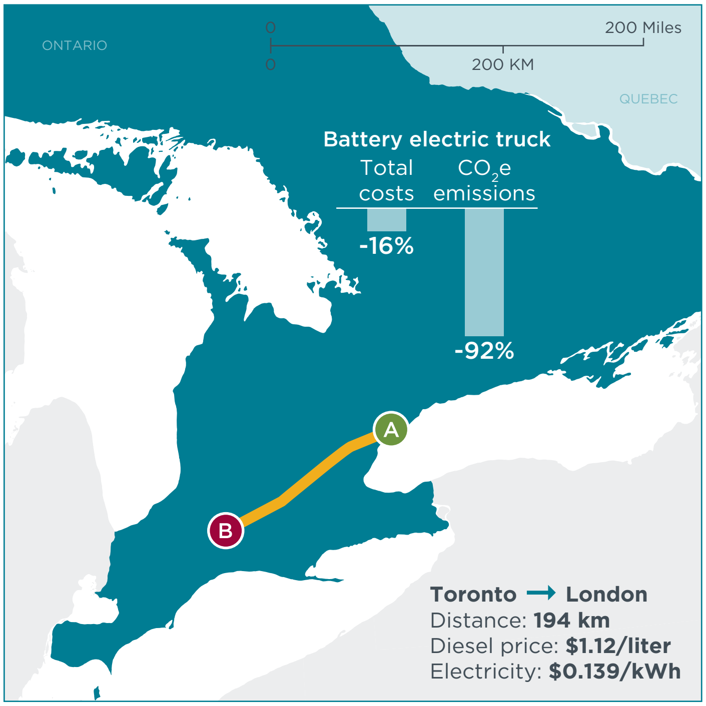

Figure 13. Difference between battery electric and diesel trucks in costs and CO_2e emissions for the Toronto-to-London corridor

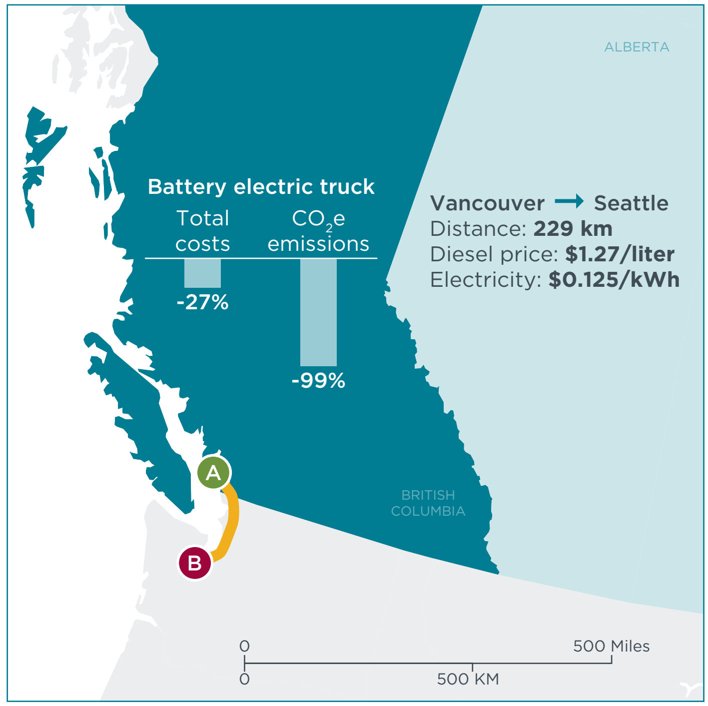

Figure 14. Difference between battery electric and diesel trucks in costs and CO_2e emissions for the Vancouver-to-Seattle corridor

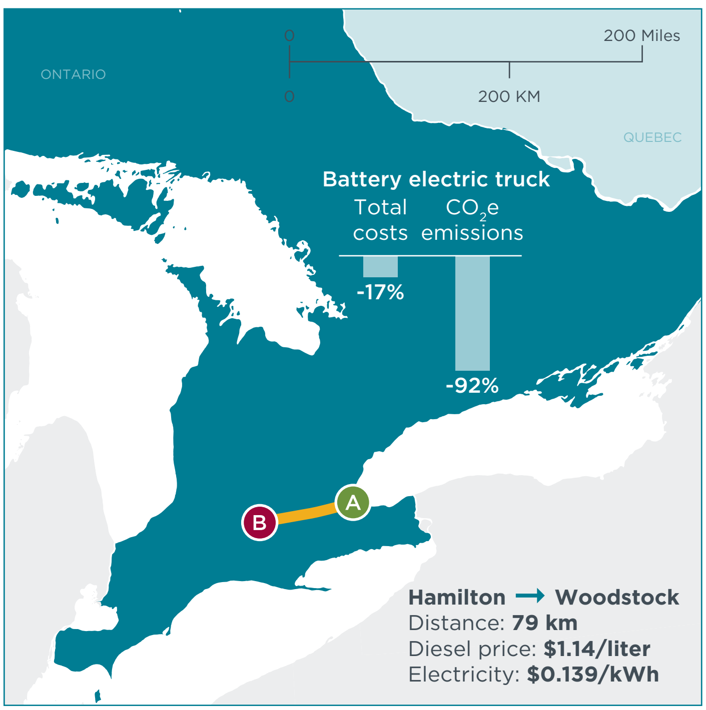

Figure 15. Difference between battery electric and diesel trucks in costs and CO_2e emissions for the Hamilton-to-Woodstock

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