
# Metro Vancouver Green Fleet Strategy Development

## Life Cycle Costing and Emissions Tool for Procurement of Low Emission Fleet Vehicles

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# Disclaimer

This report was produced as part of the UBC Sustainability Scholars Program, a partnership between the University of British Columbia and various local governments and organisations in support of providing graduate students with opportunities to do applied research on projects that advance sustainability across the region.

This project was conducted under the mentorship of Metro Vancouver's staff. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of Metro Vancouver or the University of British Columbia.

# Executive Summary

The transportation industry represents a major source of greenhouse gas (GHG) emissions in Canada. To reduce tailpipe emissions, the industry must shift towards electrification. This report will perform a comparative analysis of the various low emission vehicle options and evaluate the environmental impact and life cycle cost (LCC). To estimate the life cycle emissions (LCE) of light, medium and heavy-duty vehicles, GREET life cycle assessment software has been used. GREET was developed by Argonne National Laboratory in partnership with the US Department of Energy, and evaluates the Greenhouse gases, Regulated Emissions, and Energy used in Transportation of conventional and low emission vehicle technologies. Upon setting key parameters and assumptions in GREET and running the simulation, a simplified life cycle tool was developed for Metro Vancouver (MV) with the ability to adjust key variables as needed, without the need to modify parameters within GREET. The tool considers LCC for acquiring, operating, and maintaining a vehicle over its lifetime. Some of this cost information was provided by MV and missing information was found in literature research. The results of the life cycle tool will be used to update the low emissions vehicle standard and recommend a cost-effective vehicle purchasing strategy for the MV fleet with the aim to meet corporate emissions reduction targets.

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# Abbreviations

| | |
|---|---|
| AAA | American Automobile Association |
| BEV | Battery electric vehicle |
| CNG | Compressed natural gas |
| CRS | Congressional Research Service |
| EPA | Environmental Protection Agency |
| EV | Electric vehicle |
| FCV | Fuel cell vehicle |
| GHG | Greenhouse gas |
| GREET | Greenhouse Gases, Regulated Emissions, and Energy use in Transportation Model |
| HD | Heavy-duty |
| HEV | Hybrid electric vehicles |
| ICCT | International Council on Clean Transportation |
| ICEV | Internal combustion engine vehicle |
| IPCC | Intergovernmental Panel on Climate Change |
| LCA | Life cycle assessment |
| LCC | Life cycle cost |
| LCE | Life cycle emissions |
| LD | Light-duty |
| MD | Medium-duty |
| MSRP | Manufacturer Suggested Retail Price |
| MV | Metro Vancouver |
| NRCan | Natural Resource Canada |
| OC | Operating costs |
| PHEV | Plug-in hybrid vehicle |
| PM | Preventative maintenance |
| RNG | Renewable natural gas |
| WTP | Well-to-pump |

# Introduction

The transportation industry is shifting towards electrification as the price of gasoline and diesel continue to increase and as more cities require reduction of GHG emissions to meet their climate action targets. Specifically, MV is currently considering targets to reduce GHG emissions by 45% of 2010 levels, by 2030, become carbon neutral by 2040, and operate solely zero emission vehicles by 2050. MV is considered a large fleet operator of approximately 900 fleet assets and wants to understand the total life cycle emissions reductions and cost implications of switching to low emission vehicles. Investing in electric drive vehicle technologies will significantly reduce tailpipe emissions and contribute towards these targets. Life Cycle Assessments (LCA) are used to estimate the upstream, operating, and downstream emissions of a particular process and is a very useful tool for decision making. For this analysis, the LCA software GREET has been used to model and compare the lifecycle emissions of various powertrain technologies in the light, medium and heavy-duty vehicle classes. The cost analysis will show the lifetime investment required to purchase, maintain, operate, and dispose of the vehicle. Using both the emissions and cost analysis, comparative charts were developed to illustrate the preferred powertrain type for each vehicle segment. These recommendations will be used by MV to update their low emissions vehicle standard.

# Vehicle Powertrain Technologies

In Canada, the transportation sector represents the second largest source of GHGs. Zero emission vehicles produce no tailpipe emissions and are equipped with low carbon technologies enabling operation without use of an internal combustion engine [1]. Low and zero emission vehicles can be distinguished from an internal combustion engine vehicles (ICEV) based on their major components:

- ICEVs use fossil fuels which undergo a combustion reaction inside a combustion chamber using the oxygen present in air to produce energy and carbon dioxide as well as particulate matter contaminants as a result of incomplete combustion.
- Hybrid electric vehicles (HEV) use an internal combustion engine with an electric motor. The energy recovered from regenerative braking is stored in a battery and is discharged when operated in “electric-only” mode. When compared to ICEVs, HEVs vehicles emit 20-40% less $CO_2$ emissions [2].
- Plug-in hybrid vehicles (PHEV) are also equipped with both an internal combustion engine and an electric motor, but it differs in that the batteries are larger and can be recharged by an external power source.
- Battery electric vehicles (BEV) have an on-board rechargeable battery which drives an electric motor. The efficiency of producing energy using a vehicle with an electric drive motor compared to a combustion engine, is 76% versus 16% [2]. Lithium-ion batteries are used instead of nickel-metal hydride because they have a high energy density, resulting in an overall lower weight vehicle for the same energy storage [3]. The charging time for the on-board batteries in PHEVs and BEVs will vary depending on the level of charging: 110/120 VAC (level 1), 220/240 VAC (level 2), and 480 VDC (level 3) [2].
- Fuel cell vehicles (FCV) contain a fuel cell stack which converts hydrogen fuel into electrical power using a chemical reaction which takes place on a proton exchange membrane. Under the presence of a catalyst, the hydrogen is fed to the anode while oxygen is fed to the cathode where the hydrogen ions migrate to produce water and generate electricity. To increase adoption of FCVs, vehicle ownership costs need to be more competitive and more hydrogen refueling stations need to be installed. Nickel – metal hydride batteries are used in FCVs because of their long cycle life; however, one of

the trade-offs is that they have a low energy density, resulting in an increased vehicle weight [3].

Table 1 lists the major components of the powertrain vehicles currently available.

*Table 1: Major Components Present in Each Vehicle [4]*

| | ICEV | HEV | PHEV | BEV | FCV |
|---|---|---|---|---|---|
| **Powertrain System** | X | X | X | X | X |
| **Transmission System** | X | X | X | X | X |
| **Chassis (w/o battery)** | X | X | X | X | X |
| **Traction Motor** | | X | X | X | X |
| **Generator** | | X | X | | |
| **Electronic Controller** | | X | X | X | X |
| **Fuel Cell Onboard Storage** | | | | | X |
| **Body: including interior, exterior, and glass** | X | X | X | X | X |

Tables 2 through 4 list powertrain options evaluated in the light, medium and heavy-duty vehicle segments. The vehicles are further classified by their fuel consumption, battery size and curb weight. The light-duty (LD) trucks include SUVs, vans, and trucks. The medium-duty (MD) vehicles include truck classes 3-5, while the heavy-duty (HD) vehicles include truck classes 6-8.

*Table 2: Fuel Consumption, Battery Size and Curb Weight of Light Duty Sedans*

| **Powertrain** | **ICEV** | **HEV** | **PHEV** | **BEV** | **FCV** |
|---|---|---|---|---|---|
| **Fuel Consumption (L or Le/100 km) [2]** | 8.5 | 4.8 | 2.3 | 2.2 | 3.5 |
| **Battery size [2]** | | 32 kW | 15 kWh | 61 kWh | 38 kW |
| **Curb weight (kg) [4]** | 1,445 | 1,556 | 1,684 | 1,653 | 1,654 |

*Table 3: Fuel Consumption, Battery Size and Curb Weight of Light Duty Trucks*

| **Powertrain:** | **Van** | | | **Truck** | | | **SUV** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Class:** | **ICEV** | **HEV** | **PHEV** | **ICEV** | **HEV** | **BEV** | **ICEV** | **HEV** | **PHEV** | **BEV** | **FCV** |
| **Fuel Consumption (L or Le/100 km) [2]** | 10.8 | 7.0 | 2.9 | 12.8 | 9.5 | 2.6 | 9.9 | 6.7 | 3.0 | 2.5 | 3.4 [5] |
| **Battery size [2]** | | 53 kW | 24 kWh | | 53 kW | 110 kWh | | 45 kW | 19 kWh | 72 kWh | 45 kW [5] |
| **Vehicle Curb weight (kg) [4]** | 2,724 | 2,724 | 2,724 | 2,038 | 2,198 | 2,573 | 1,762 | 1,902 | 2,052 | 2,169 | 2,029 |

*Table 4: Fuel Consumption, Battery Size and Curb Weight of Medium and Heavy-Duty Trucks*

| | **Medium Duty** | | | **Heavy Duty** | | |
|---|---|---|---|---|---|---|
| **Powertrain** | **Diesel** | **CNG/RNG** | **BEV** | **Diesel** | **CNG/RNG** | **BEV** |
| **Class** | 3-5 | 3-5 | 3-5 | 6-8 | 6-8 | 6-8 |
| **Fuel Consumption (L or Le/100 km)** | 48.7 [6] | 41 [7] | 5.6 [8] | 61.1 [6] | 46.3 [7] | 20.7 [7] |
| **Battery size** | | | 250 kWh [9] | | | 400 kWh [10] |
| **Curb weight (kg)** | 3,632 [11] | 4,834 [12] | 5,632 | 6,000 [11] | 7,202 [12] | 9,200 |

## Hydrogen Production Pathways in British Columbia

FCVs operate using hydrogen as a fuel. British Columbia has 4 main sources of hydrogen: natural gas, water, biomass and $H_2$ by-products from industrial plants [13]. In the process of steam reforming, methane gas is mixed with high temperature steam in the presence of a catalyst to produce hydrogen and carbon dioxide [13]. In the process of water electrolysis, electricity is supplied to an electrolyser to separate the hydrogen atoms in the $H_2O$ molecule. In B.C., the main source of that electricity is hydroelectricity, thus making it a greener option for hydrogen production.

$$H_2O \xrightarrow{\text{Electricity}} H_2 + \frac{1}{2}O_2$$

The biomass undergoes a gasification reaction in which the biomass is partially oxidized using steam as the oxidizing agent to produce CO and $H_2$ [13]. To increase the yield of hydrogen production, a water-gas shift reaction takes place to convert the CO into $CO_2$ and $H_2$ [13]. When combined with carbon capture storage, the hydrogen produced from biomass and natural gas becomes net carbon neutral.

$$C_6H_{12}O_6 + O_2 + H_2O\ (\mathrm{g}) \xrightarrow{\text{Heat}} CO + CO_2 + H_2$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

Hydrogen by-products from industrial facilities may be considered in the long term, but at this point much of the hydrogen has not been captured effectively [13].

## Understanding the GREET Model

GREET is a LCA software developed by Argonne National Laboratory in partnership with the U.S. Department of Energy, which evaluates the Greenhouse gases, Regulated Emissions, and Energy use in Transportation model of conventional and low emission vehicle technologies [14]. In order to evaluate the total LCE of each vehicle, both the fuel cycle and vehicle cycle were analyzed. Figure 1 illustrates the system boundary of the fuel and vehicle cycle. The fuel cycle is defined as well-to-pump (WTP) which includes production and transportation of feedstock; production, transportation, storage and distribution of fuel, and vehicle operation [15]. Vehicle operation includes fuel combustion, evaporation, brake, and tire wear. The vehicle cycle includes processing of the raw material recovery and extraction, material processing and fabrication, manufacturing and assembly of the components and vehicle disposal and recycling [15]. It should be noted that the emissions from the transportation of the materials between each stage in the vehicle cycle are excluded from the model [14]. The GREET 1 and GREET 2 software tools were used to collect the emissions data for the fuel cycle and the vehicle cycle, respectively. GREET 2 is only available for LD cars, SUVs and trucks and utilizes data inputted into GREET 1 to give the combined results of the fuel and vehicle cycle. For the scope of this project, the fuel types compared in GREET 1 were: conventional gasoline, low-sulfur diesel, compressed natural gas (CNG), renewable natural gas (RNG), gaseous hydrogen (whose primary energy source is natural gas) and electricity.

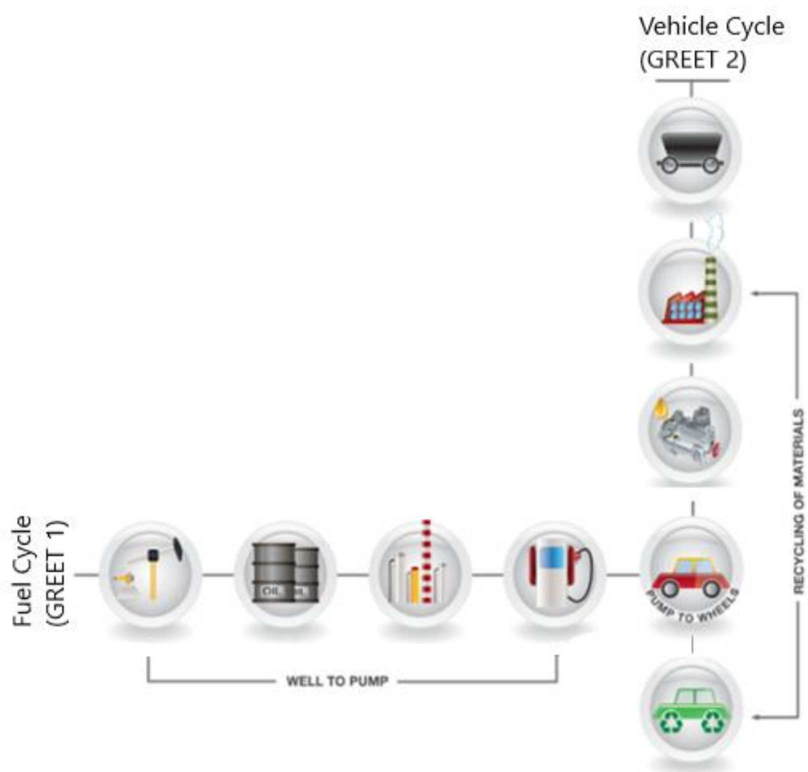


Figure 1: Fuel and Vehicle Cycle System Boundary [15]

## GREET 1: Fuel Cycle

Upstream emissions are produced during the combustion of process fuels, fuel production and distribution of fuel to the end user. To calculate the upstream fuel cycle emissions, energy consumed at each stage in the fuel cycle is estimated based on the specified allocation of fuel burned at each stage [15]. The energy consumption per energy throughput is combined with the emission factors for the specified combustion technology to determine the emissions for each upstream stage [15]. The GREET 1 excel spreadsheet includes emission factors for different combustion technologies fueled by various process fuels (Tab "EF") [15]. The heating values, densities and weight ratios of carbon and sulfur are used to calculate the $CO_2$ and $SO_x$ combustion emission factors (Tab "Fuel_Specs") [15]. By default, GREET uses the low heating values because energy contained in water vapour cannot be recovered from fuel combustion from vehicles [15].

Non-combustion emissions are also considered in the model, these include volatile organic compound emissions from fuel spills during transportation/distribution and methane ($CH_4$) emissions from natural gas leaks during transmission and processing [15].

The electricity generation mix needs to be specified for transportation use and stationary use. Transportation use defines the electricity mix for grid-connected electric vehicles; here hydropower was selected because over 86% of electricity in Vancouver is generated from hydro [13]. The stationary use specifies the electricity for upstream fuel production; here the "user defined" category was selected and data for the Canadian electricity mix was entered (as shown in Table 5).

*Table 5: Composition of Canada's 2020 Electricity Mix [16]*

| **Fuel Source** | **Composition** |
|---|---|
| **Residual oil** | 1.3 % |
| **Natural gas** | 9.4 % |
| **Coal** | 7.4 % |
| **Nuclear power** | 14.8 % |
| **Biomass** | 1.7 % |
| **Others** | 65.4 % |

A calculation is then performed to establish the emissions of each pollutant per energy of fuel throughput for each upstream stage in the fuel cycle [15]. Each upstream stage is assigned an efficiency to account for fuel losses due to leaks and/or evaporation (Tab "Fuel_Prod_TS") [15]. The emissions from each upstream stage are then aggregated to obtain a final well-to-pump emissions value for each pollutant. The total GHGs include $CO_2$, $CH_4$ and $N_2O$. These pollutants are then multiplied by their respective global warming potentials (obtained from the IPCC tables) and summed to obtain the total GHG value with units of $CO_2$-equivalent.

The GREET 1 model assumes FCVs fueled by hydrogen are equipped with a proton exchange membrane fuel cell [15]. The benefit of using hydrogen as a fuel (in FCV), is the $CO_2$ emissions can be localized at the central $H_2$ plant instead of emitted in the environment while driving the vehicle. The concentrated $CO_2$ emissions can be sequestered via carbon capture technologies to produce saleable carbon by-products. To estimate the upstream fuel cycle emissions of fuel cell vehicles, the source of hydrogen production must be defined in GREET 1. $CO_2$ capture has not yet been adopted in all natural gas plants, so the model was simulated for three hydrogen feedstock sources: natural gas using $CO_2$ sequestration, natural gas without $CO_2$ sequestration, and water electrolysis via hydroelectricity. GREET assumes that 84% of the total $CO_2$ from natural gas plants would be sequestered because some of the $CO_2$ will be lost to the atmosphere [17]. The GREET 1 model uses the assumption that 357 kWh of electricity is required to capture 1 ton of carbon [15]. Using the life cycle tool, the user can select whether to include $CO_2$ capture technologies or not, and the new fuel cycle emissions will be calculated.

## GREET 2: Vehicle Cycle

GREET 2 uses the inputs defined in GREET 1 to determine the emissions produced during manufacturing of the vehicle. This is done using a series of iterative loops which are run in the background, the logic is shown in Figure 2 below. For example, emissions from process fuels and electricity are defined in GREET 1 and are used during the vehicle manufacturing stages.

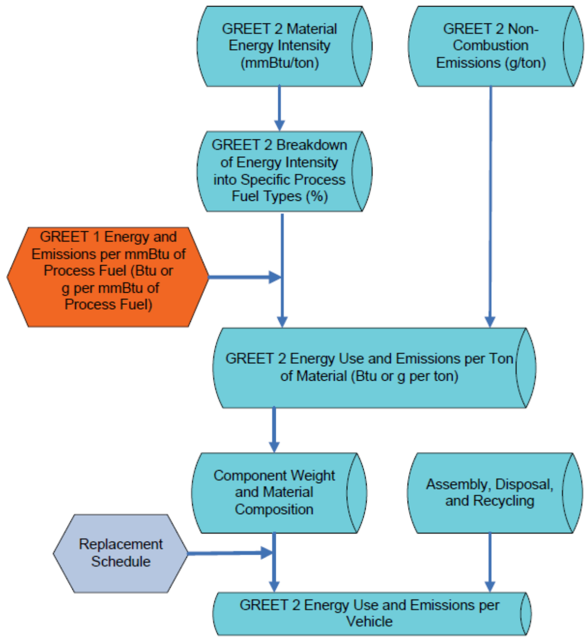


Figure 2: Logic for GREET 2 Vehicle Cycle [14]

To calculate the upstream vehicle cycle emissions, the weight and material composition of each major component must be specified. The major components include the body, chassis, battery, fluids, powertrain, transmission, motor, controller, and generator [14]. The selected weights for each vehicle type are shown in Table 6 below.

*Table 6: Total Vehicle Curb Weight (lbs) [4]*

| | ICEV | HEV | PHEV | BEV | FCV |
|---|---|---|---|---|---|
| **LD Sedan** | 3,183 | 3,429 | 3,710 | 3,643 | 3,644 |
| **LD SUV** | 3,882 | 4,191 | 4,521 | 4,434 | 4,471 |
| **LD Truck** | 4,491 | 4,843 | 5,275 | 5,408 | 5,243 |

The replacement schedule is defined for specific components which will be replaced within the vehicle's lifetime for maintenance (see Table 7). The GREET 2 model assumes these replaced components will be recycled back into their original raw material to be used again in the vehicle cycle [14]. The lead-acid batteries are used for start-up and accessory load for the vehicle and it is assumed it would be replaced twice over the vehicle lifetime [14]. The manufacturer's warranty is valid for 8 years or 160,000 km which provides a good indication of the life of rechargeable batteries, thus allowing the model to assume that the lithium-ion battery in BEVs and PHEVs and the nickel metal hydride battery in HEVs and FCVs will last the entire lifetime without requiring replacement [14]. From this input data, the model will estimate the emissions from the vehicle materials, battery production and fabrication, fluid production and disposal (coolant, engine oil, adhesives, and windshield, steering, brake, and transmission fluid), and vehicle assembly, painting, disposal and recycling [14].

*Table 7: Replacement Schedule of Components over the Vehicle Lifetime [4]*

| | Tires | Lead-Acid battery | Engine oil | Brake fluid | Transmission fluid | Powertrain coolant | Windshield fluid |
|---|---|---|---|---|---|---|---|
| **LD Sedan** | 3 | 2 | 39 | 3 | 1 | 3 | 19 |
| **LD SUV** | 4 | 2 | 44 | 4 | 1 | 4 | 22 |
| **LD Truck** | 4 | 2 | 44 | 4 | 1 | 4 | 22 |

## Estimation of Emissions from Vehicle Operation

Using the 2021 Fuel Consumption Guide from Natural Resources Canada (NRCan), information was obtained regarding the fuel consumption of 2021 model-year LD vehicles. The emission factors of gasoline, diesel and natural gas were provided by the 2020 BC Best Practices Methodology for Quantifying GHG Emissions and were used to quantify the amount of $CO_2$-eq emitted for every liter of fuel burned [18]. Each model vehicle consumes different amounts of fuel to travel a specified distance, resulting in varying combustion emissions. A vehicle's fuel consumption is affected by driving speed and acceleration, vehicle age, weather, traffic conditions, drivetrain, and use of powered accessories. The data provided in the guide is generated in a controlled laboratory environment performed by the manufacturer. Manufacturers are now required to use a 5-cycle testing procedure to better simulate driving conditions

[2]. The vehicles are driven 6,000 km before testing these 5 driving conditions: city, highway, cold weather, use of air conditioners, and high speed with quick accelerations and braking [2].

LD vehicle emissions are measured by the vehicle chassis dynamometers on a per-km basis as specified by the EPA standards [15]. HD vehicle emissions are measured by the engine dynamometers on a per-brake-horsepower-hr basis [15]. These emissions are then converted to a per-km basis. NRCan does not require manufacturers to submit fuel consumption data for vehicles with a gross vehicle weight rating greater than 3,856 kg [2]. The fuel consumption of MD and HD vehicles is application specific as many vehicles in this class are equipped with auxiliary hydraulics and power systems which places additional fuel loads on the fuel system, hence this data set was obtained from MV fleet data. Using this fuel economy combined with the emission factors of diesel and natural gas, the tailpipe emissions from MD and HD trucks were calculated.

For the scope of this study, the vehicles in the guide were separated into two categories; cars and trucks, and then subdivided by powertrain: ICEV, HEV, PHEV, and BEV. Figure 3 shows how the vehicles classes were grouped into sedans, LD trucks, SUVs and Vans. Fuel cell vehicles were not yet available on the NRCan guide, so this information was obtained directly from the manufacturer's website. The average combined fuel consumption of each subcategory was used as the input for the life cycle tool to estimate fuel costs. The combined fuel rating assumes 55% city and 45% highway driving [2]. The fuel consumption of electric vehicles is expressed in units of kWh per 100km. To accurately compare electric vehicles, this number is converted to gasoline liters equivalent using a factor of 8.9kWh per liter of gasoline [2].

| Cars | |
|---|---|
| **Vehicle class** | **Interior volume** |
| Two-seater (**T**) | n/a |
| Minicompact (**I**) | less than 2,405 L (85 cu. ft.) |
| Subcompact (**S**) | 2,405–2,830 L (85–99 cu. ft.) |
| Compact (**C**) | 2,830–3,115 L (100–109 cu. ft.) |
| Mid-size (**M**) | 3,115–3,400 L (110–119 cu. ft.) |
| Full-size (**L**) | 3,400 L (120 cu. ft.) or more |
| Station wagon<br>Small (**WS**)<br>Mid-size (**WM**) | <br>less than 3,680 L (130 cu. ft.)<br>3,680–4,530 L (130–159 cu. ft.) |

| Light trucks | |
|---|---|
| **Vehicle class** | **Gross vehicle weight rating** |
| Pickup truck<br>Small (**PS**)<br>Standard (**PL**) | <br>less than 2,722 kg (6,000 lb.)<br>2,722–3,856 kg (6,000–8,500 lb.) |
| Sport utility vehicle<br>Small (**US**)<br>Standard (**UL**) | <br>less than 2,722 kg (6,000 lb.)<br>2,722–4,536 kg (6,000–10,000 lb.) |
| Minivan (**V**) | less than 3,856 kg (8,500 lb.) |
| Van<br>Cargo (**VC**)<br>Passenger (**VP**) | <br>less than 3,856 kg (8,500 lb.)<br>less than 4,536 kg (10,000 lb.) |
| Special purpose vehicle (**SP**) | less than 3,856 kg (8,500 lb.) |

Figure 3: Light-Duty Vehicle Class Specifications [2]

# Life Cycle Tool Development

Using the GREET LCA simulations, upstream and downstream emissions were estimated for light, medium and heavy-duty vehicles. Assumptions were made to design a new excel-based model to easily manipulate variables to re-calculate the new LCE and LCC. This tool is more user-friendly and takes away the complexity of re-running the GREET model every time a change is required.

## Assumptions to Calculate Life Cycle Emissions

The GREET 2 model estimates the vehicle cycle emissions for LD sedans, SUVs and trucks based on the vehicle's curb weight. To distinguish between the GVWR, the curb weight includes only the weight of the vehicle, fluids and its components and does not include the cargo or passengers [14]. To meet the scope of this project, a linear regression was performed to estimate the vehicle cycle emissions for LD vans, and MD and HD trucks. To estimate the curb weight of battery electric trucks, the weight of the battery was added to the curb weight of a diesel truck using the energy density of a lithium-ion battery at 0.125 kWh/kg [19]. By using a linear approximation, the user is able to input a new curb weight and the life cycle tool will estimate the new vehicle cycle emissions.

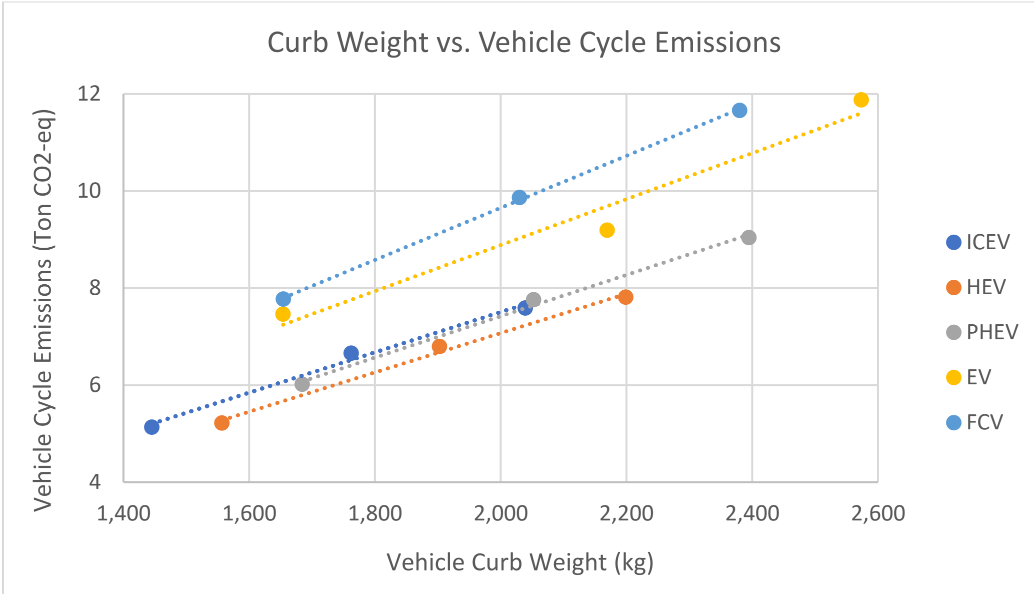


Figure 4: Vehicle Curb Weight vs. Vehicle Cycle Emissions

The vehicle cycle emissions include the components, fluids, and batteries, however in order to analyze the emissions contributions from battery assembly and disposal, this component was separated from the total vehicle cycle. The emissions from batteries is related to the material composition and size. To obtain the battery emissions for LD vans, and MD and HD trucks, again a linear regression analysis was performed for Ni-MH and Li-ion batteries. Here battery emissions were plotted against battery size using the data from LD vehicles (see Figure 5). It was defined that HEVs and FCVs contained nickel-metal hydride batteries and PHEVs and BEVs contained lithium-ion batteries. By using a linear approximation, the user can input a new battery size and the life cycle tool will estimate the battery emissions.

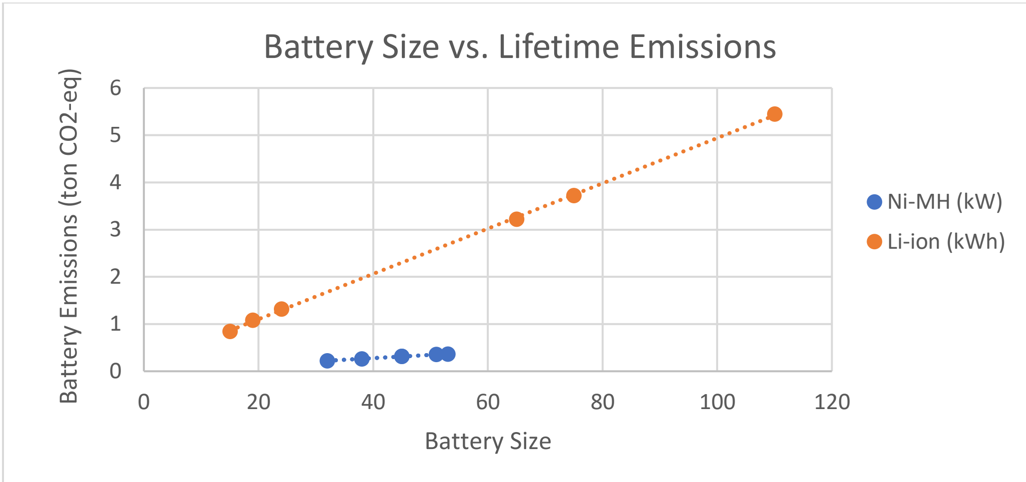


Figure 5: Battery Size vs. Battery Emissions

## Assumptions to Calculate Life Cycle Cost

To accurately compare the cost of low emission vehicles to that of internal combustion engine vehicles, we must compare them based on their total LCC. This method considers the upfront, operating, and environmental costs to owning and using a vehicle. For the scope of this analysis, the operating costs include fuel and electricity, insurance, and maintenance. The time value of money must be considered because the initial and periodic costs are incurred at different times. Before these costs can be added together, they must first be brought to the same time period. The capital vehicle costs are assumed to be financed and not purchased in one lump sum. For this reason, the capital cost is amortized over the life of the vehicle, with a 3% interest rate. And the cash flows of the annual operating costs (OC) are brought forward over the vehicle lifetime to calculate their expected future value.

$$FV = OC \times \frac{[(1+i)^n - 1]}{i}$$

### Estimation of Capital Costs

Using the 2021 model vehicles from the NRCan fuel consumption guide, the MSRP values were obtained from the manufacturer's website for each vehicle. All vehicles were then grouped by class and sub-grouped by fuel type. The average MSRP from each sub-group was used as the representative capital cost. The high-performance vehicles were removed from the vehicle list because the high cost would skew the average. Additionally, MV customizes their fleet vehicles, so the provided outfitting costs were added to the capital costs. The approximate outfitting costs for sedans, SUVs, LD trucks, and vans are $2,000, $2,000, $5,000, and $20,000, respectively.

The cost of an EV charging station was included in the capital cost of BEVs and PHEVs. The charger would likely need to be replaced every 10 years and will incur network and maintenance fees. It was assumed that 15% of the MSRP would be allocated towards the premium for EV charging stations. Note that the infrastructure costs have not been included in this analysis.

### Estimation of Operating Costs

Maintenance costs include routine, preventative maintenance (PM), and unexpected repairs arising from operational environment or accidental damage. First, the MV fleet data was grouped by the equipment number and the costs incurred each year were summed to obtain the annual maintenance cost. Next, the annual cost from 2010 to 2020 for each vehicle category and fuel type was averaged. Using the average annual cost divided by the annual distance driven, the maintenance cost per km driven was obtained. Finally, a 25% factor was applied to this value to account for parts missing on PM work orders and were therefore not yet entered into the spreadsheet. For some of the low emission vehicles which were not included in the fleet maintenance data provided by MV, literature values were consulted. The American Automobile Association (AAA) performs an annual study to estimate the cost of ownership of various LD vehicle classes. From their 2020 data, the maintenance costs per km were obtained for ICE sedans, SUVs, vans, and trucks and HEV and BEV sedans. The maintenance costs of low emission LD work vehicles (according to AAA values) were scaled down relative to the MV ICE fleet data, as shown in Table 8 below. The maintenance cost of BEVs are lower than ICEVs because BEVs do not need to incur the costs of oil changes, exhaust maintenance, spark plugs, fuel injectors or transmission repairs [20]. When compared to ICEVs, the brakes in an BEV could last over 300,000 km due to reduced wear from regenerative braking technology. Fuel cell vehicles are quite new on the market and there is limited research available on the maintenance cost. However, the Advanced Vehicle Cost and Energy-Use Model has estimated a 20% reduction in maintenance costs compared to ICEVs [21].

*Table 8: Maintenance Costs % Difference Relative to ICEV [22]*

| ICEV | HEV | PHEV | BEV | FCV |
|---|---|---|---|---|
| | -36% | -42% | -47% | -20% |

A similar approach was used for MD and HD trucks, but a study performed by the University of Victoria was consulted to determine the maintenance cost difference relative to ICEVs because the internal components are much different. If the CNG fuel is not dried sufficiently, there will be water present which results in bad fuel quality [23]. Unlike their diesel counterparts, CNG trucks do not incur the cost of exhaust aftertreatment but they do incur the maintenance of spark plugs, filter changes from bad fuel and frequent CNG tank inspections [23]. Literature studies indicate that, when compared to diesel vehicles, the repair and maintenance costs for natural gas vehicles are about the same.

The insurance costs were calculated using MV's fleet data. For some of the low emission vehicles not listed in the fleet data, assumptions were made to estimate the annual insurance costs. The insurance cost of FCVs were assumed to be the same as BEVs. Based on the fleet data, the insurance cost of BEVs were 40.5% higher than ICEVs. This factor was applied to calculate the insurance premium of battery-electric LD, MD, and HD trucks. The insurance costs of MD and HD CNG trucks were assumed to be the same as their diesel counterpart.

To estimate the lifetime fuel and electricity costs, an annual price escalation factor was applied to the current market fuel prices over a 10-year period (see Table 9). These values can be found in the "Assumptions" tab of the life cycle tool and can be updated as needed.

*Table 9: Estimated Fuel and Escalation Prices used in the Life Cycle Tool*

| | |
|---|---|
| **B.C. electricity price** | $ 0.12/ kWh |
| **Electricity price escalation** | 3% |
| **Gasoline price** | $1.49 /L |
| **Gasoline price escalation** | 4.9% |
| **Diesel Price** | $1.37 /L |
| **Diesel price escalation** | 5.5% |
| **Hydrogen Price** | $12.75 /kg |
| **Hydrogen price escalation** | 4.9% |
| **Natural Gas price** | $1.3 /kg |
| **Natural Gas price escalation** | 1.9% |

The environmental tax was applied to both upstream and tailpipe $CO_2$-eq emissions. MV is currently adopting a lifetime environmental cost of $150/ton $CO_2$-eq.

The estimated residual value of the vehicle at the end of life was subtracted from the total LCC. This salvage value was calculated based on a 30% 1$^{st}$ year depreciation ($R_1$) and a 20% subsequent year depreciation ($R_2$). The estimated residual value after 10 years was calculated to be 9.4% of the original capital cost, using the MV Standard Economic Assumptions.

$$Estimated\ Residual\ \% = [(1 - R_1) \times (1 - R_2)]^n$$

## Tool User Guide

Using the emissions data from GREET, costing data from MV fleet, and the NRCan 2021 fuel consumption guide, an excel spreadsheet, titled “Life Cycle Tool”, was created to allow users to easily manipulate variables in order to re-calculate the new life cycle emissions and costs while providing a visual comparison between technologies. In the first tab of the spreadsheet, labelled “Assumptions”, the user can manipulate any of the inputs used for the calculations and the tool will recalculate the new LCE and LCC. An overview of these variables is shown in Table 10 below, a more detailed snapshot can be found in Appendix C. The maintenance cost per vehicle category is given in units of $/km, so the user may input a new lifetime distance and the tool will calculate the new maintenance cost over the vehicle life. In cell C26, the user can select whether to include carbon capture when extracting hydrogen from natural gas. The fuel cost and price escalation factors can also be changed from the “Assumptions” tab to update the fuel costs. The end-of-life salvage value is based on the first and second-plus years’ depreciation amount, which is defined in cell G14 and G15.

*Table 10: Assumptions Used as Inputs for the Life Cycle Tool*

| | |
|---|---|
| **Annual distance** | 20,000 km |
| **Vehicle life** | 200,000 km |
| **Planned life** | 10 years |
| **$H_2$ from natural gas with carbon capture?** | No |
| **$CO_2$ sequestration rate** | 83.8 % |

In the tab labelled “Life Cycle Tool”, rows 10 and 11 is where the user can select the battery size and vehicle curb weight, which will update the battery and vehicle cycle emissions. By changing the fuel economy of the vehicle, located in row 5, the new fuel cost will be calculated.

The results section summarizes the lifecycle emissions and costs using illustrative charts to easily compare vehicles and make procurement decisions. The 6 charts can be found in the tabs labelled: Sedan_Em, Sedan_Cost, Truck_Em, Truck_Cost, MD_HD_Em, and MD_HD_Cost and are shown in the Results section.

## Analysis of Results

From the 2021 fuel economy ratings published by NRCan and the fuel and vehicle cycle emissions estimated in the life cycle tool using GREET, Figures 6, 8 and 10 were developed to illustrate the comparison between the low emission vehicle technologies of the light, medium and heavy-duty vehicle segments. Using the MV fleet data and literature resources, the life cycle cost for all suitable low emission vehicle options were analyzed and are presented in Figures 7, 9 and 11. A more detailed analysis can be found in Appendices D through F.

The low emission powertrain options available in the sedan vehicle segment include HEV, PHEV, BEV and FCV. Figure 6 compares the LCE of the LD sedans. In ICEVs, tailpipe emissions represent the largest portion of the total LCE, amounting to 75%. This number gets reduced to 67% and 56% for HEVs and PHEVs, respectively. In BEVs, battery assembly and disposal accounts for 40% of the total LCE. When comparing the emissions from electricity, FCVs using electrolysis utilize 8% whereas BEVs contribute 6% of the total LCE. In FCVs, the main source of GHG emissions comes from the vehicle cycle, producing 7.6 tonnes over the vehicle lifetime. Next, looking at the cost analysis in Figure 7, it is shown that HEVs have the lowest LCC. The vehicles which use plug-in charging have a low fuel cost because electricity from hydroelectricity is quite cheap. These vehicles also incorporate the EV charging station cost in their LCC making them slightly higher compared to HEVs. FCVs have the highest LCC because of its relatively new technology, the capital and maintenance costs as well as the price of hydrogen fuel are quite high compared to other vehicle technologies.

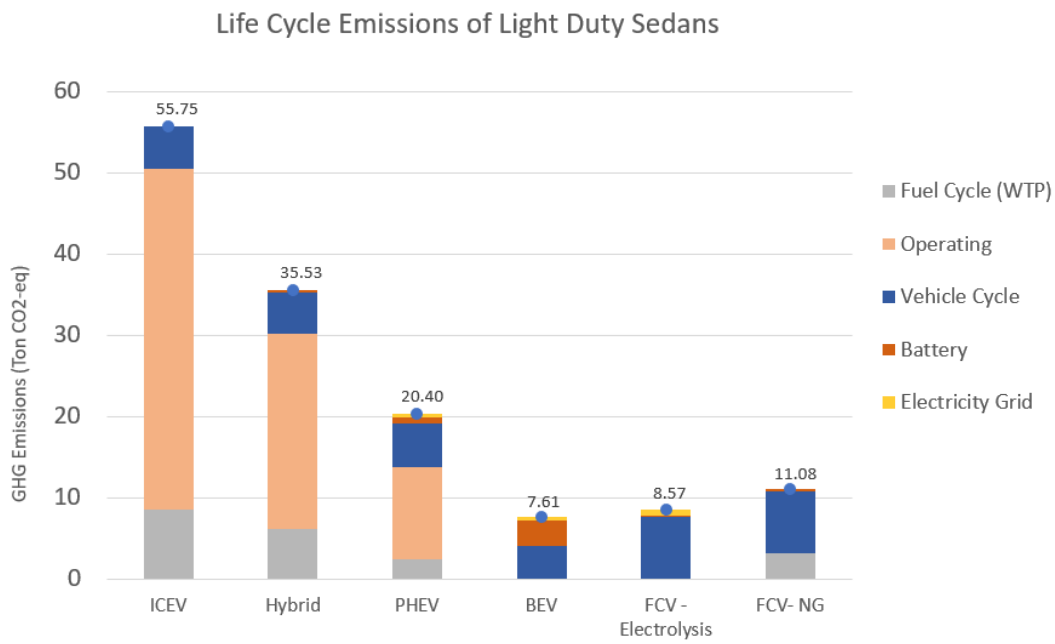


Figure 6: Life Cycle Emissions of Light-Duty Sedans

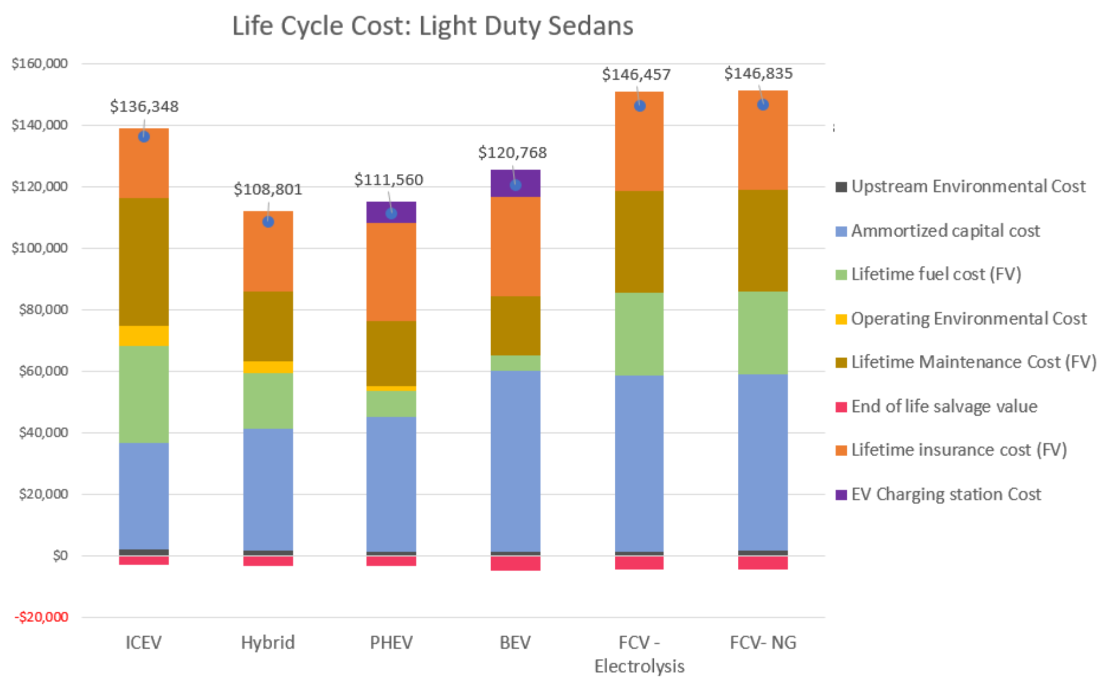


Figure 7: Breakdown of Life Cycle Cost of Light-Duty Sedans

The low emission powertrain options available in the LD work vehicle classes include HEV and PHEV vans, HEV and BEV trucks and HEV, PHEV, BEV and FCV SUVs. Figure 8 compares the LCE of the LD work vehicles. Compared to ICEVs, the tailpipe emissions from HEVs are reduced by 35%, 26%, 32% for vans trucks and SUVs, respectively. The tailpipe emissions from HEVs are further reduced by 59% and 55% for PHEV vans and SUVs. In battery-electric trucks and SUVs, the battery assembly and disposal accounts for 45% and 36% of the total LCE. Similar to LD sedans, the main source of GHG emissions in FCVs comes from the vehicle cycle, producing 9.6 tonnes over the vehicle lifetime. From the cost comparison in Figure 9, the maintenance cost of BEVs are roughly half that of ICEVs. Of all the vehicle technologies, ICEVs have the highest environmental cost. PHEV vans and SUVs and HEV trucks have the lowest LCC.

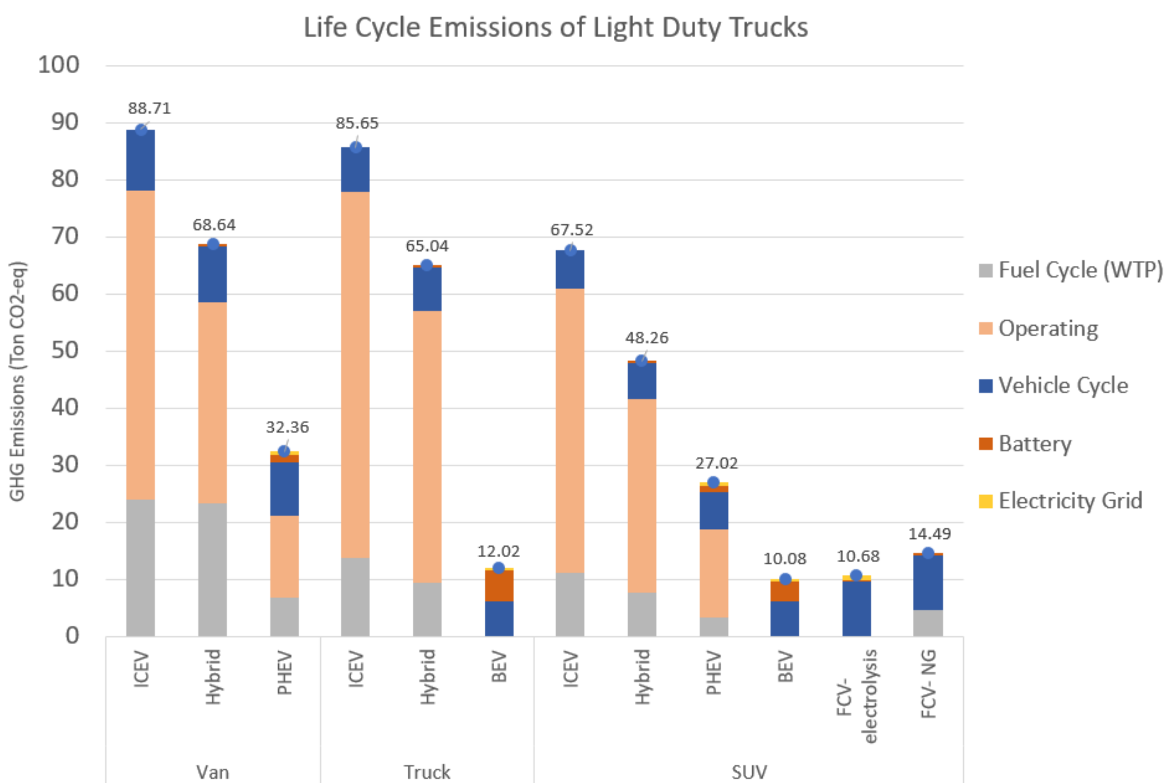


Figure 8: Life Cycle Emissions of Light-Duty Trucks

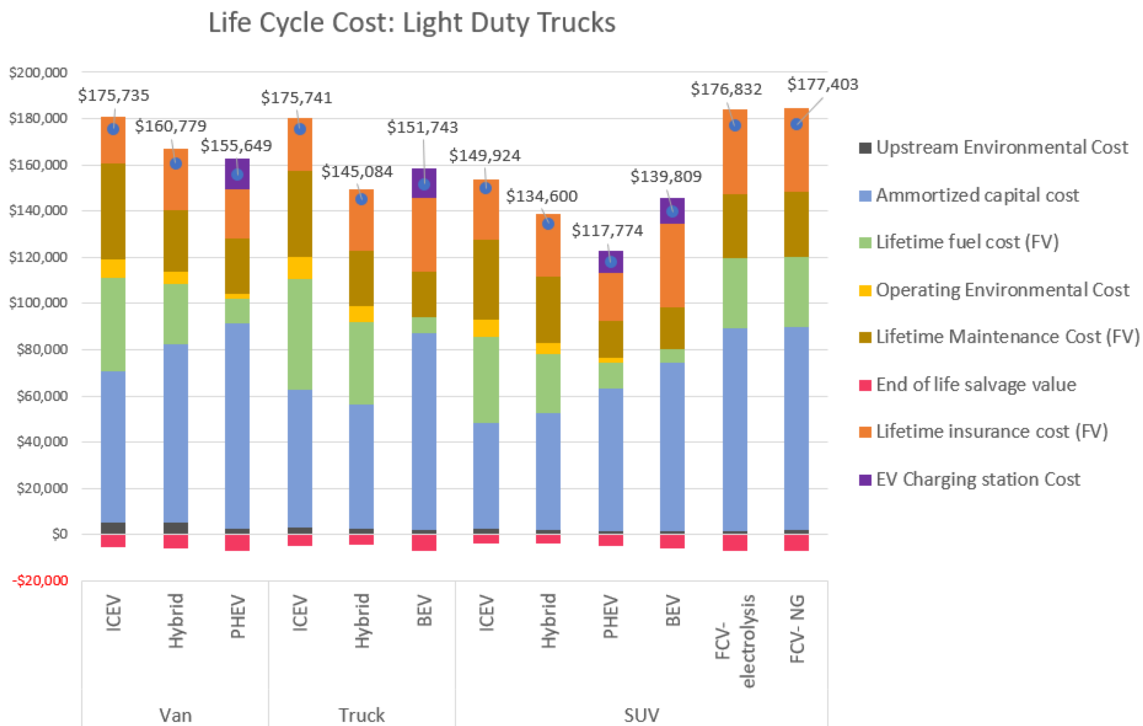


Figure 9: Breakdown of Life Cycle Cost of Light-Duty Trucks

CNG trucks produce 35% and 42% lower tailpipe emissions than diesel for the MD and HD vehicle segments, respectively. Figure 10 shows that the fuel cycle emissions of diesel and CNG are relatively similar, whereas RNG reduces fuel cycle emissions by approximately 90%. The emissions from the vehicle cycle are dependent on the curb weight, which is slightly higher in natural gas trucks. For this reason, the vehicle cycle emissions are 20-35% more in RNG and CNG trucks. BEVs produce large emissions from battery assembly and disposal, thus RNG trucks become the lowest LCE option with a 92% reduction in lifetime GHG emissions. Figure 11 shows that the CNG MD and HD vehicles have a lower LCC compared to their diesel counterpart and this is attributed towards the low price of natural gas fuel in Vancouver. There is an incremental cost added to the CNG vehicles to account for the additional components which may include the ignition system and CNG fuel tank. As well, the current market rate for renewable natural gas fuel has a 30% premium over the CNG fuel. BEV trucks are relatively new on the market, and the current market value for capital cost is assumed to be 50% more than the diesel truck. The fuel cost savings and capital cost assumption makes battery-electric trucks the lowest LCC in both the MD and HD vehicle segments.

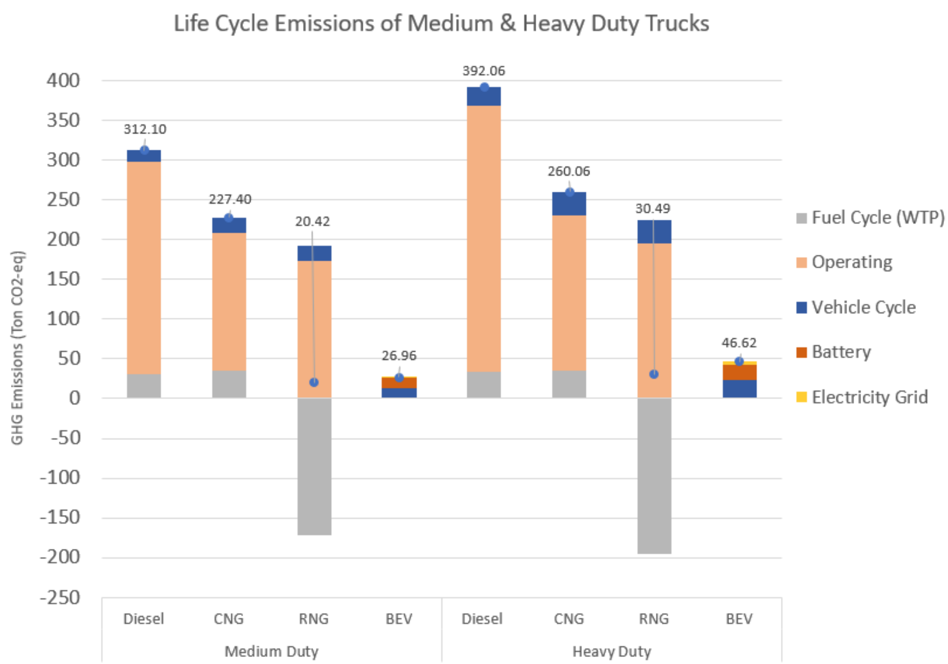


Figure 10: Life Cycle Emissions of Medium and Heavy-Duty Trucks

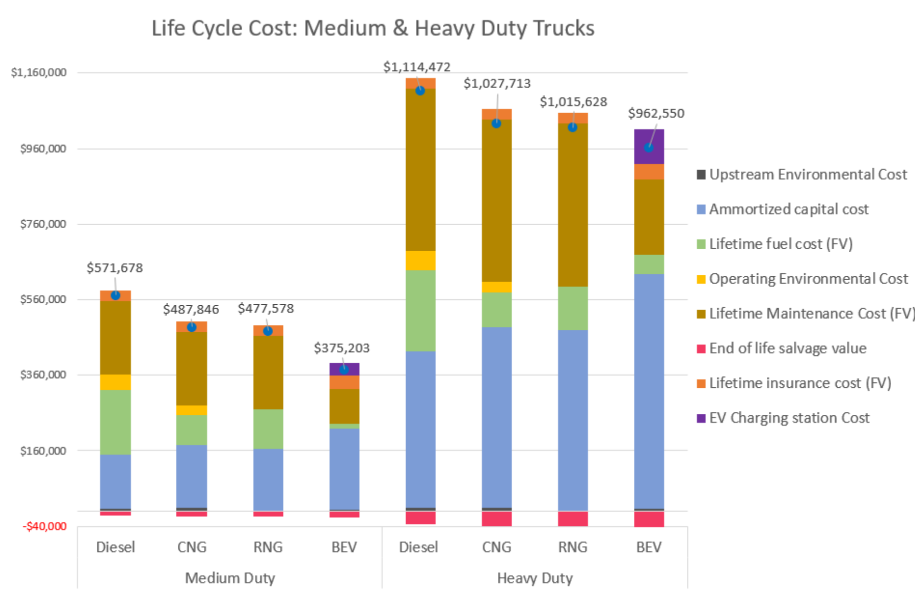


Figure 11: Breakdown of Life Cycle Cost of Medium and Heavy-Duty Trucks

## Recommendations

MV is committed to meeting the climate action targets by decarbonizing their fleet, however vehicle procurement needs to be assessed on a case-by-case basis. While the results of the life cycle emissions LCE show a distinct powertrain technology that offers the lowest life cycle emissions, this is not the case for total LCC. Table 11 summarizes the lowest LCE and LCC powertrain technologies for each of the vehicle classes and shows the emissions impacts of selecting power train technologies with lowest LCC, as well as financial impacts of selecting power train technologies with the lowest LCE.

*Table 11: Summary of LCE and LCC for Each Vehicle Class*

| Vehicle Class | Lowest LCE Technology | LCE reduction from ICEV [tCO2e / %] | LCE Differential from Lowest LCC [tCO2e / %] | Lowest LCC Technology | LCC reduction from ICEV [$ / %] | LCC Differential from Lowest LCE [$ / %] |
|---|---|---|---|---|---|---|
| **Sedan** | BEV | 48 ton /86% | 28 ton/80% | HEV | $27,500/20% | $12,000/11% |
| **SUV** | BEV | 57 ton /85% | 17 ton/63% | PHEV | $32,000/21% | $22,000/18% |
| **Van** | PHEV | 56 ton /63% | -- | PHEV | $20,000/11% | -- |
| **Truck** | BEV | 73 ton /85% | 53 ton/82% | HEV | $30,600/17% | $6,600/5% |
| **MD Truck** | RNG | 290 ton /93% | 6.5 ton /24% | BEV | $196,000/34% | $102,000/27% |
| **HD Truck** | RNG | 360 ton /92% | 16 ton /35% | BEV | $152,000/14% | $53,000/5.5% |

When considering the LCE of the LD sedans, BEVs would be the preferred selection, followed by PHEVs. Compared to ICEVs, the BEV and PHEVs represent an 86% and 63% reduction in GHG emissions. When evaluating emissions from FCVs, the method of obtaining hydrogen is crucial, as well as if carbon capture is included or not. Hydrogen extraction using electrolysis is more energy intensive than BEVs and emit far less emissions than hydrogen extracted from steam methane reforming. When considering the LCC of the LD sedans, HEVs and PHEVs would be the preferred selection. Although BEVs have the lowest LCE, the large capital cost of the BEVs in addition to the cost of the charging station makes BEVs unfavourable. The difference in cost between the HEVs and PHEVs is $2,800 over the vehicle lifetime. This is a small price to pay to receive a 63% reduction in GHG emissions from PHEVs, compared to only 36% emissions reductions from HEVs.

Looking at the LCE of LD trucks, the BEV option is the preferred choice for trucks and SUVs, representing an 85% GHG reduction from ICEVs. Currently there are no BEVs on the market for vans, so the preferred choice in this vehicle segment would be PHEVs, representing a 63% reduction in GHG emissions compared to ICEVs. On the basis of LCC, PHEVs would still be the recommended choice for vans. However, it is no longer favourable to invest in BEV SUVs due to the large capital cost and cost of the EV charging stations. When compared to BEVs, PHEVs represent a lifetime savings of $22,000 with a 60% GHG reduction, thus it is preferred to use PHEVs for the SUV segment. For LD trucks, HEVs have a lifetime savings of $6,600 compared to BEVs but only a 24% reduction in LCE. It may be worthwhile to pay this small price difference and invest in battery electric trucks to receive the higher GHG reduction of 85%.

RNG would be the preferred choice for MD and HD trucks based on LCE, representing a 92% GHG reduction when compared to ICEVs. However, BEVs are favourable in terms of LCC, even with the higher cost of capital and EV charging stations, because the low cost of hydroelectricity results in a larger lifetime fuel savings. BEVs in the MD and HD segments represent a $196,000 and $152,000 lifetime savings compared to ICEVs, respectively. The incremental cost of MD and HD trucks using natural gas fuel are expected to decrease in the future, so it is recommended to re-evaluate the RNG fuel option in 5 years.

## Benchmarking to Validate Results

To validate the LCE results obtained from the developed life cycle tool, the emissions values were cross-checked with literature values. Figure 12 below depicts the comparison of emissions from the life cycle tool using the GREET model with 3 LCAs done by: Argonne National Laboratory, Congressional Research Service (CRS), and the International Council on Clean Transportation (ICCT) to validate the results obtained for the LD sedans. The LCE from HEV and FCVs were compared to the Argonne results and the BEVs and PHEVs were compared to the CRS and ICCT results. The differences between the LCAs come from the assumptions made to run the simulation. Argonne assumes a lifetime driving distance of 160,000 miles whereas ICCT assumes 150,000 km, CRS assumes 278,000 km, and the GREET simulation uses 200,000 km [14] [24] [25]. In all four results, the LCE from ICEVs were the highest. The emissions from battery assembly and disposal are dependent on the size of the lithium-ion battery, the composition of raw materials, and frequency of replacement. ICCT assumes an 18.4 kWh for PHEVs and 30kWh battery for BEVs, whereas the GREET simulation assumes a 15 kWh for PHEVs and 61 kWh battery for BEVs [25]. CRS does not specify the battery size used in their electric vehicle simulation. The life cycle tool assumes a linear relationship between battery size and emissions using the default GREET assumptions. Emissions from battery manufacturing can range from 50 to 500 kg $CO_2$/kWh; ICCT assumes 175 kg $CO_2$/kWh for its estimation of battery emissions [25]. Based on these differences, the battery emissions for BEVs and PHEVs in the life cycle tool are lower than that in the CRS and ICCT results.

The emissions from the vehicle cycle are dependent on the specified vehicle size; the results were relatively similar between the life cycle tool and the 3 reference models. There is a slight difference in the emissions from vehicle operation. This is due to the assumptions made regarding the fuel economy of the vehicles. Fuel economy data used in the life cycle tool was obtained from the NRCan 2021 fuel consumption guide whereas Argonne used 2010 model-year vehicles [14]. The tailpipe emissions of HEVs are relatively similar between Argonne and life cycle tool. ICCT assumes that PHEVs are operated in electric-only mode during short trips, resulting in much lower tailpipe emissions when compared to the results of the life cycle tool [25]. The tailpipe emissions of PHEVs from the life cycle tool are similar to that of the CRS results.

There is a large variation in the emissions from the fuel cycle in the PHEV, BEV and FCV which is due to the different emission intensities of the defined electricity grid. CRS uses the 2017 average US electricity grid, whereas ICCT using the 2015 average European electricity grid and the life cycle tool defines stationary electricity use as the 2020 Canadian mix (Table 5) and transportation use as hydroelectricity [24] [25]. For this reason, the fuel cycle emissions from the PHEVs and BEVs are minimal in the life cycle tool and are predominant in the CRS and ICCT results. The Argonne results use the 2005 average US electricity grid which again results in much higher fuel cycle emission compared to the GREET simulation for FCVs [14].

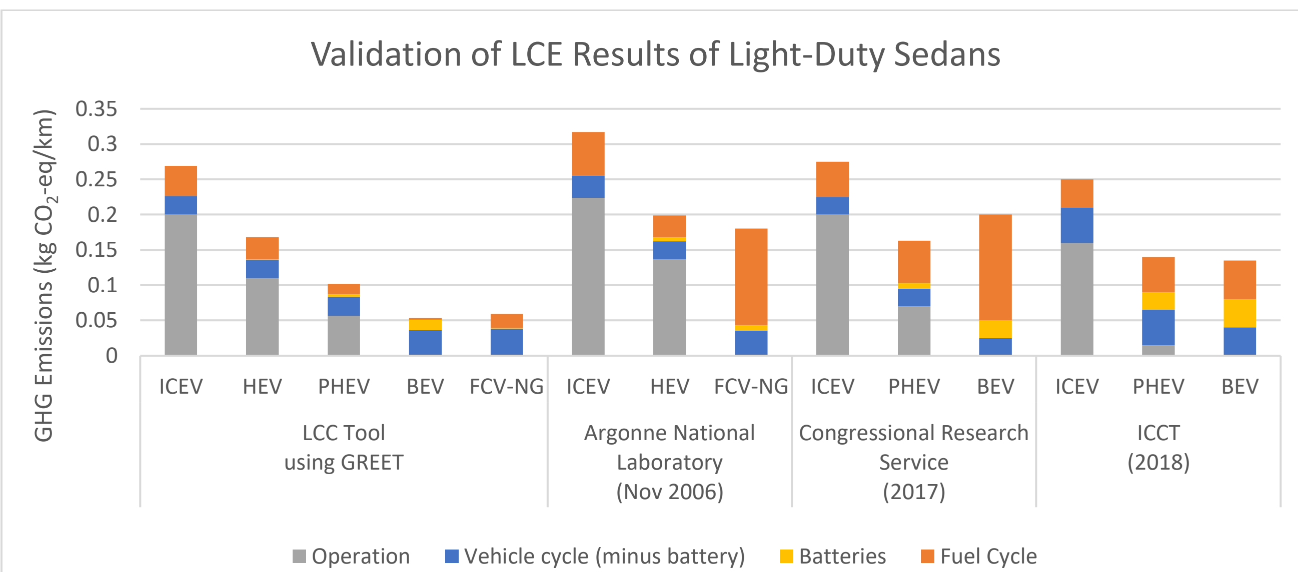


Figure 12: Benchmarking of LCE Results of Light-Duty Sedans

To validate the LCC results obtained from the developed life cycle tool, the costs were compared to literature values. Figures 13-16 depict the comparison of costs from the life cycle tool using the GREET model with 2 LCAs done by: Argonne National Laboratory and AAA. To establish consistency in this comparison, the environmental costs and EV charging station costs were removed from the life cycle tool. AAA assumes an annual driving distance of 15,000 miles averaged over 5 years whereas Argonne assumes 15-year vehicle life, and the GREET simulation uses 20,000 km over 10 years. Relative to ICEVs, the LCC of HEVs are lower and BEVs are higher in both the life cycle tool and AAA.

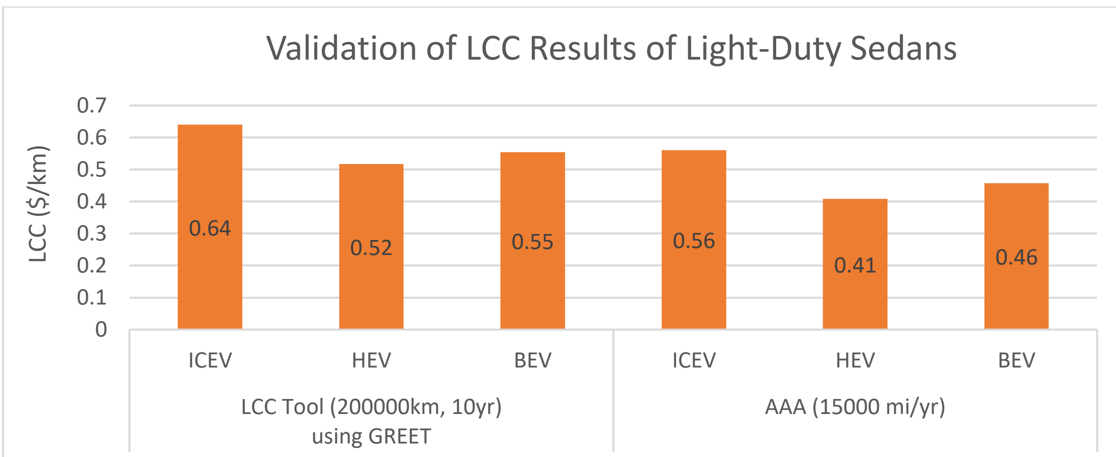


Figure 13: Benchmarking of LCC Results of Hybrid and Battery-Electric Sedans

Argonne represents MD and HD trucks by a 2020 model-year class 4 delivery truck and class 8 day cab tractor, respectively. Delivery trucks and tractors are simple in application with no auxiliary hydraulic systems and equipment which could explain the big difference in cost. The labour costs have been removed for comparison purposes. There is a large variation in what Argonne uses as its capital cost and what is used in the life cycle tool, overall Argonne is on the low side. The cost of electricity impacts the lifetime fuel cost; hydroelectricity is much cheaper than the US. Electricity mix.

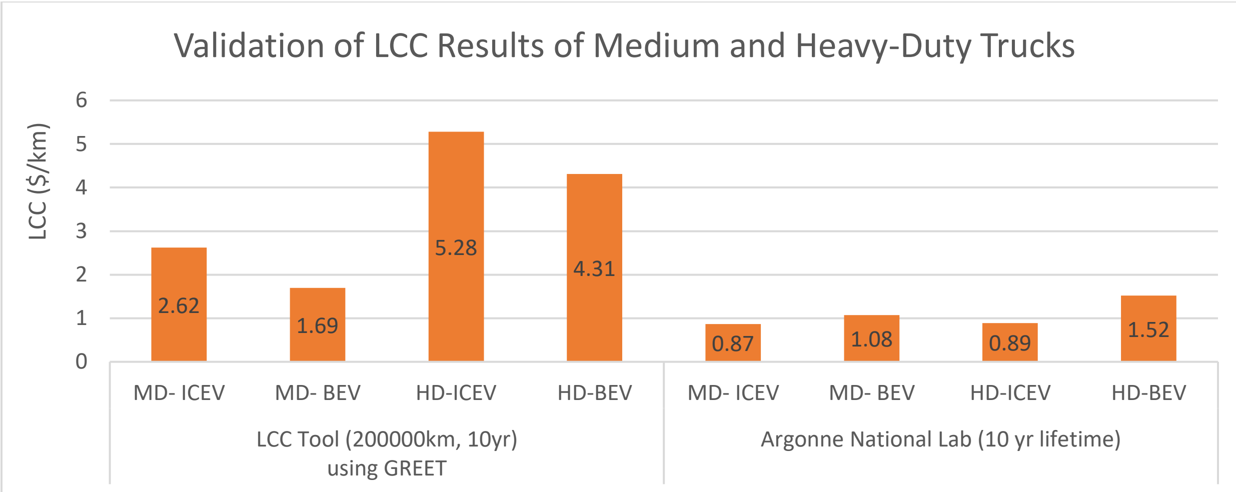


Figure 14: Benchmarking of LCC Results of MD and HD Trucks

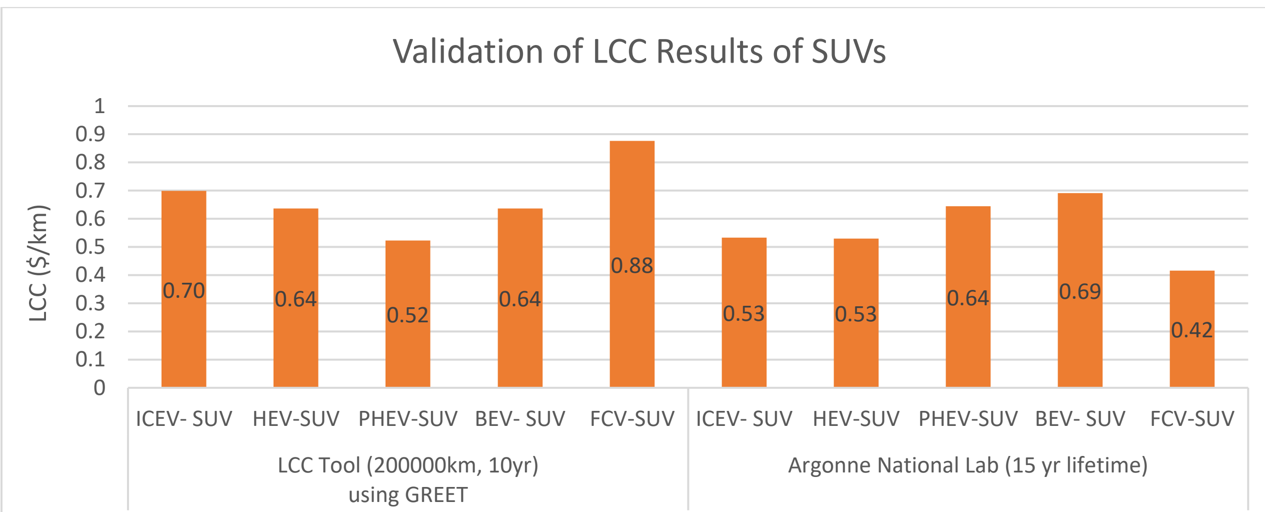


Figure 15: Benchmarking of LCC Results of SUVs

# Conclusion

The LCE of low emission vehicles were compared by totalling the emissions from the vehicle cycle, fuel cycle, and vehicle operation. The life cycle costs were compared by totalling the capital cost, foregone interest, fuel, maintenance, insurance, and environmental cost over a ten-year life. From the analysis in this document, it is recommended that MV electrify their fleet on the basis on LCE and LCC. The preferred low emission vehicles for the LD sedans are PHEVs. They are slightly costlier than the than HEVs but provide a greater GHG reduction relative to ICEVs. For the LD trucks, PHEVs should be used for vans and SUVs, while trucks should pay the small price difference to receive the GHG benefit from BEVs. Based on both emissions and cost reductions, the MD and HD fleet vehicles should be switched to BEVs.

When compared to studies preformed in other literature reviews, the results of this analysis are relatively comparable. The major difference comes from the upstream fuel cycle of electric vehicles. In this study, there are minimal emissions because hydroelectricity is used as the source of electricity, however in literature the U.S. and European electricity mix are used resulting in a higher allocation of emissions. Based on the difference in battery size and emission intensities, the emissions from battery manufacturing in the life cycle tool are lower than that in the literature results. There are also some minor differences in emissions from vehicle operation which is attributed to the defined vehicle fuel consumption.

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# Appendix A – Battery GHG Emissions by Size and Type

*Table 12: Battery Type and Size [4]*

| | HEV (Ni-MH) | PHEV (Li-ion) | BEV (Li-ion) | FCV (Ni-MH) |
|---|---|---|---|---|
| **LD Sedan** | 32 kW | 15 kWh | 65 kWh | 38 kW |
| **LD SUV** | 45 kW | 19 kWh | 75 kWh | 45 kW |
| **LD Truck** | 53 kW | 24 kWh | 110 kWh | 51 kW |

*Table 13: Life Cycle GHG Emissions from Batteries (g CO2-eq) [4]*

| | ICEV **(Pb-acid)** | HEV **(Pb-acid + Ni-MH)** | PHEV **(Pb-acid + Li-ion)** | EV **(Pb-acid + Li-ion)** | FCV **(Pb-acid + Ni-MH)** |
|---|---|---|---|---|---|
| **LD Sedan** | 32,044 | 222,096 | 845,382 | 3,219,865 | 259,582 |
| **LD SUV** | 47,621 | 316,938 | 1,080,966 | 3,724,575 | 316,938 |
| **LD Truck** | 47,621 | 361,921 | 1,314,754 | 5,447,756 | 354,424 |

## Appendix B – MV Fleet Maintenance and Insurance Costs

*Table 14: Maintenance Costs of MV Fleet Vehicles [6]*

| Diesel | $/km |
|---|---|
| Truck HD | 1.87 |
| Truck MD | 0.85 |
| **Gasoline** | |
| Car | 0.22 |
| SUV | 0.14 |
| Truck LD | 0.14 |
| Van | 0.18 |
| **HEV** | |
| SUV | 0.12 |
| **PHEV** | |
| SUV | 0.06 |

*Table 15: Annual Insurance Premiums of MV Fleet Vehicles [6]*

| Diesel | $/year |
|---|---|
| Truck HD | 2,486 |
| Truck MD | 2,301 |
| **Gasoline** | |
| Car | 1,997 |
| SUV | 2,253 |
| Truck LD | 1,998 |
| Van | 1,773 |
| **HEV** | |
| Car | 2,252 |
| SUV | 2,345 |
| **PHEV** | |
| Car | 2,807 |
| SUV | 1,847 |
| **BEV** | |
| Car | 2,807 |

# Appendix C – Life Cycle Tool Assumptions

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Conversion Factors** | | | | | | | |
| | 1 USD | 1.21 | CAD | **Emission factors** [8] | | | |
| | 1 mile | 1.609 | km | | Gasoline (LD Sedan) | 2.462 | kg CO2-eq/L |
| | 1 kWh = | 3.6 | MJ | | Gasoline (LD Truck) | 2.495 | kg CO2-eq/L |
| | 1L gasoline = | 8.9 | KWh | | Diesel | 2.738 | kg CO2-eq/L |
| | | | | | Natural gas | 3.089 | kg CO2-eq/kg |
| | | | | | RNG | 0.2932 | kg CO2-eq/GJ |
| | Annual distance | 20000 | km | | | | |
| | Vehicle life | 200000 | km | | BC Environmental Cost | 150 | $/ton |
| | Planned life | 10 | years | | | | |
| **Electricity** | | | | | Ammortization interest rate | 3.00% | |
| | BC electricity price | 0.1174 | $/kWh average [1] | | | | |
| | Electricity price escalation | 3.00% | | | | | |
| | 1 GJ electricity | 3 | kg $CO_2$ [2] | | First Year Depreciation | 30.00% | |
| | Li-ion Battery energy density | 0.125 | kWh/kg [3] | | Second+ Year(s) Depreciation | 20.00% | |
| **Gasoline** | | | | | Estimated Residual Percentage | 9.40% | |
| | Price gasoline | 1.49 | $/L | | | | |
| | Gasoline price escalation | 4.90% | | | | | |
| **Diesel** | | | | | | | |
| | Price diesel | 1.37 | $/L | | | | |
| | Diesel price escalation | 5.50% | | | | | |
| **Hydrogen** | | | | | | | |
| | Price H2 | 12.75 | $/kg [4] | | | | |
| | H2 price escalation | 4.90% | | | | | |
| | 1 kg H2 | 39 | kWh [5] | | | | |
| | H2 from NG with carbon capture? | yes | | | | | |
| | CO2 sequestration rate | 83.86% | | | | | |
| | | | | | | | |
| **Natural Gas** | | | | | | | |
| | Price Natural Gas | 1.3 | $/kg CNG [6] | | | | |
| | Natural Gas price escalation | 1.90% | | | | | |
| | DLe to NG conversion | 1.462 | DLe/kg Natural gas [7] | | | | |

# Appendix D – Detailed Vehicle Category Comparison for Sedans

| Powertrain | ICEV | HEV | PHEV | BEV | FCV - Electrolysis | FCV- Natural Gas |
|---|---|---|---|---|---|---|
| Fuel Consumption (L or Le/100 km) | 8.51 | 4.86 | 2.30 | 2.20 | 3.48 | 3.48 |
| Lifetime Fuel Consumption (L or Le or kg) | 17,019 | 9,727 | 4,600 | | 6,950 | 6,950 |
| | | | | | | |
| **Emissions (ton CO2-eq)** | | | | | | |
| WTP Fuel Cycle | 8.58 | 6.23 | 2.49 | 0 | 0 | 3.23 |
| Electric Grid Emissions | 0 | | 0.44 | 0.42 | 0.72 | 0 |
| Vehicle Cycle minus Battery | 5.27 | 5.13 | 5.29 | 4.13 | 7.59 | 7.59 |
| Battery | | 0.22 | 0.85 | 3.05 | 0.26 | 0.26 |
| Tailpipe Emissions | 41.90 | 23.95 | 11.33 | 0 | 0 | 0 |
| **Total Life Cycle Emissions (ton CO2)** | **55.75** | **35.53** | **20.40** | **7.61** | **8.57** | **11.08** |
| | | | | | | |
| **Costs** | | | | | | |
| Upstream Environmental Cost | 2,077 | 1,737 | 1,361 | 1,140 | 1,285 | 1,662 |
| EV Charging Station Cost | | | 6,567 | 8,830 | | |
| Capital Cost | 34,594 | 39,615 | 43,780 | 58,865 | 57,222 | 57,222 |
| Fuel Cost | 31,747 | 18,145 | 8,353 | 5,280 | 27,135 | 27,135 |
| Operating Environmental Cost | 6,285 | 3,592 | 1,698 | 0 | 0 | 0 |
| Insurance Cost | 22,889 | 25,816 | 32,179 | 32,179 | 32,179 | 32,179 |
| Maintenance Cost | 41,526 | 23,069 | 21,130 | 19,190 | 33,221 | 33,221 |
| End of Life Salvage Value | -2,772 | -3,174 | -3,508 | -4,717 | -4,585 | -4,585 |
| **Total Life Cycle Cost** | **$136,348** | **$108,801** | **$111,560** | **$120,768** | **$146,457** | **$146,835** |

# Appendix E – Detailed Vehicle Category Comparison for Light-Duty Work Vehicles

| **Powertrain** | **Van** | | | **Truck** | | | **SUV** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Class | ICEV | HEV | PHEV | ICEV | HEV | BEV | ICEV | HEV | PHEV | BEV | FCV-electrolysis | FCV- NG |
| Fuel Consumption (L or Le/100 km) | 10.84 | 7.07 | 2.90 | 12.87 | 9.55 | 2.69 | 9.97 | 6.78 | 3.07 | 2.50 | 3.42 | 3.42 |
| Lifetime Fuel Consumption (L or Le or kg) | 21,680 | 14,133 | 5,800 | 25,741 | 19,100 | | 19,931 | 13,550 | 6,142 | | 6,840 | 6,840 |
| | | | | | | | | | | | | |
| **Emissions (ton CO2-eq)** | | | | | | | | | | | | |
| WTP Fuel Cycle | 23.98 | 23.24 | 6.72 | 13.65 | 9.40 | 0 | 11.19 | 7.68 | 3.33 | 0 | 0 | 4.61 |
| Electric Grid Emissions | 0 | 0 | 0.56 | 0 | 0 | 0.52 | 0 | 0 | 0.64 | 0.48 | 0.80 | 0 |
| Vehicle Cycle minus Battery | 10.64 | 9.77 | 9.29 | 7.76 | 7.62 | 6.06 | 6.60 | 6.46 | 6.67 | 6.02 | 9.57 | 9.57 |
| Battery | | 0.36 | 1.32 | | 0.36 | 5.45 | | 0.31 | 1.06 | 3.58 | 0.31 | 0.31 |
| Tailpipe Emissions | 54.09 | 35.26 | 14.47 | 64.23 | 47.65 | 0 | 49.73 | 33.81 | 15.33 | 0 | 0 | 0 |
| **Total Life Cycle Emissions (ton CO2)** | **88.71** | **68.64** | **32.36** | **85.65** | **65.04** | **12.02** | **67.52** | **48.26** | **27.02** | **10.08** | **10.68** | **14.49** |
| | | | | | | | | | | | | |
| **Costs** | | | | | | | | | | | | |
| Upstream Environmental Cost | 5,192 | 5,006 | 2,683 | 3,212 | 2,608 | 1,803 | 2,668 | 2,168 | 1,754 | 1,512 | 1,602 | 2,173 |
| EV Charging Station Cost | | | $13,310 | | | $12,837 | | | $9,211 | $10,899 | | |
| Capital Cost | $65,217 | $77,244 | $88,734 | $59,282 | $53,612 | $85,578 | $45,648 | $50,422 | $61,408 | $72,663 | $87,792 | $87,792 |
| Fuel Cost | 40,441 | 26,364 | 10,515 | 48,018 | 35,628 | 6,460 | 37,180 | 25,275 | 11,237 | 5,921 | 30,328 | 30,328 |
| Operating Environmental Cost | 8,113 | 5,289 | 2,170 | 9,633 | 7,148 | 0 | 7,459 | 5,071 | 2,298 | 0 | 0 | 0 |
| Insurance Cost | 20,322 | 26,676 | 21,176 | 22,906 | 26,676 | 32,202 | 25,823 | 26,882 | 21,176 | 36,303 | 36,303 | 36,303 |
| Maintenance Cost | 41,673 | 26,388 | 24,170 | 37,439 | 23,707 | 19,720 | 34,802 | 28,821 | 15,608 | 18,331 | 27,841 | 27,841 |
| End of Life Salvage Value | -5,226 | -6,190 | -7,111 | -4,751 | -4,296 | -6,858 | -3,658 | -4,040 | -4,921 | -5,823 | -7,035 | -7,035 |
| **Total Life Cycle Cost** | **$175,735** | **$160,779** | **$155,649** | **$175,741** | **$145,084** | **$151,743** | **$149,924** | **$134,600** | **$117,774** | **$139,809** | **$176,832** | **$177,403** |

## Appendix F – Detailed Vehicle Category Comparison for Medium and Heavy-Duty Trucks

| **Vehicle type:** | **Medium Duty** | | | | **Heavy Duty** | | | |
|---|---|---|---|---|---|---|---|---|
| **Powertrain** | **Diesel** | **CNG** | **RNG** | **BEV** | **Diesel** | **CNG** | **RNG** | **BEV** |
| Class | 3-5 | 3-5 | 3-5 | 3-5 | 6-8 | 6-8 | 3-5 | 6-8 |
| Fuel Consumption (L or Le/100 km) | 48.7 | 41 | 41 | 5.6 | 61.1 | 46.3 | 46.3 | 20.67 |
| Lifetime Fuel Consumption (L or Le or kg) | 97,400 | 56,087 | 56,087 | | 122,200 | 63,337 | 63,337 | |
| | | | | | | | | |
| **Emissions (ton CO2-eq)** | | | | | | | | |
| WTP Fuel Cycle | 30.96 | 34.65 | -172.33 | 0 | 33.08 | 34.96 | -194.61 | 0 |
| Electric Grid Emissions | | | | 1.08 | | | | 3.97 |
| Vehicle Cycle minus Battery | 14.46 | 19.50 | 19.50 | 13.52 | 24.40 | 29.45 | 29.45 | 22.88 |
| Battery | | | | 12.36 | | | | 19.77 |
| Operating Emissions | 266.68 | 173.25 | 173.25 | 0 | 334.58 | 195.65 | 195.65 | 0 |
| **Total Lifetime Emissions (ton CO2)** | **312.10** | **227.40** | **20.42** | **26.96** | **392.06** | **260.06** | **30.49** | **46.62** |
| | | | | | | | | |
| **Costs** | | | | | | | | |
| Upstream Environmental Cost | 6,812 | 8,122 | | 4,043 | 8,622 | 9,661 | | 6,993 |
| EV Charging station Cost | | | | 32,197 | | | | 93,255 |
| Capital Cost | 143,097 | 166,148 | 166,148 | 214,646 | 414,466 | 478,438 | 478,438 | 621,700 |
| Fuel Cost | 171,806 | 79,474 | 103,316 | 13,415 | 215,551 | 89,748 | 116,672 | 49,527 |
| Operating Environmental Cost | 40,002 | 25,988 | | 0 | 50,187 | 29,347 | | 0 |
| Insurance Cost | 26,374 | 26,374 | 26,374 | 37,078 | 28,497 | 28,497 | 28,497 | 40,062 |
| Maintenance Cost | 195,054 | 195,054 | 195,054 | 91,025 | 430,364 | 430,364 | 430,364 | 200,836 |
| End of life salvage value | -11,468 | -13,315 | -13,315 | -17,202 | -33,216 | -38,343 | -38,343 | -49,825 |
| **Total Lifetime Cost** | **$571,678** | **$487,846** | **$477,578** | **$375,203** | **$1,114,472** | **$1,027,713** | **1,015,628** | **$962,550** |