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TECHNICAL REPORT

**Assessment of Energy Efficiency Ratios
of Electric and Fuel Cell Light Duty
Vehicles in Canada – Final Report**

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Executive Summary

The proposed *Clean Fuel Regulations* (CFR) require that primary suppliers of gasoline and diesel fuel reduce the carbon intensity of those fuels that they produce or import. Compliance must be achieved by using credits that can be created by the primary supplier or purchased from other credit creators. In addition to actions that reduce the carbon intensity of the fuel across its lifecycle, other credit creating activities include supplying low-carbon fuels and specified end-use fuel switching in transportation. Credits that can be created by end-use fuel switching to electric vehicles are calculated based on energy efficiency ratios (EERs).

EER is a dimensionless ratio of vehicle efficiencies using different fuels. Energy efficiency ratios are sometimes called Energy Effectiveness Ratio or Energy Economy Ratio, however all three terms mean the same thing and are all represented as EER. EERs have been used by the California Low Carbon Fuel Standard (LCFS), the Oregon Clean Fuel Program, and the British Columbia Renewable and Low-Carbon Fuel Requirements Regulation.

A robust and transparent methodology for calculating EERs within the Canadian context could be beneficial for the deployment of different climate change policies and regulations in the transport sector. Natural Resources Canada (NRCan) has asked the Clean & Energy Efficient Transportation (CEET) program of the National Research Council Canada (NRC) to undertake a study to analyze/quantify a range of EERs for light duty vehicles (LDV). EERs are calculated for several LDV classes (Compact, Full-size, Mid-size, Minivan, and SUV: Small, SUV: Standard). Three technologies were considered: Plug-in Hybrid Electric Vehicles (PHEVs), Battery Electric Vehicles (BEVs) and hydrogen Fuel Cell Vehicles (FCVs).

Several different LDV propulsion technologies are available in Canada. Internal combustion engine vehicles (ICEV) are the most widespread technology in use today. Combustion engines are typically fueled by either gasoline or diesel. Battery electric vehicles (BEVs) are powered by rechargeable batteries. Plug-in Hybrids use both the battery and gasoline for propulsion, and the battery can be recharged by plugging the vehicle in. Hydrogen Fuel Cell Vehicles are powered by onboard hydrogen that is converted into electricity in a fuel cell, which is used to power an electric motor. FCVs also use batteries to accommodate temporary high power demands.

The project consisted of three main tasks: 1) a literature review, 2) development of a transparent and consistent EER calculation methodology, 3) calculation of EERs for several LDV classes for BEVs, PHEVs, and FCVs.

The literature review describes various studies that consider the climatic effects of the various technologies. There is a definite trend of increased fuel consumption at low temperatures across all technologies, which comes from an efficiency loss, and an increased heating load. More work is required to determine quantitative relationships to account for the increased fuel consumption

A methodology was developed with the goal of being clear and consistent. The method was applied to the dataset created from the NRCan, the US Environmental Protection Agency (EPA), and

GoodCarBadCar.net (GCBC) data. Fuel consumption ratings that are publicly available from NRCan and the EPA are used to calculate energy efficiency ratios for each combination of technology and LDV class considered. Sales data from GCBC is used to calculate sales weighted EERs. Data from the three sources is combined to create a dataset to compute the EER values.

The sales-weighted EER value of a specific vehicle model is estimated relative to the sales-weighted fuel efficiency of the ICEVs in the same class. When sales data is available sales weighted average EERs are calculated in addition to the simple average EERs for each vehicle class and technology combination.

The calculated EERs are summarized in a table for the 6 LDV classes (Compact, Full-size, Mid-size, Minivan, SUV: Small, SUV: Standard) and three propulsion technologies (BEV, PHEV, FCV). In general there is good agreement with the presented values and values adopted by BC, Oregon, and California and with other values from literature. Sales data for PHEVs was not available, so no sales-weighted EERs are calculated. The EER values presented in this report have a much higher granularity, as values are presented across 6 LDV classes and 3 propulsion technologies.

Table 1: Summary of EER values by technology and vehicle class.

Class	Technology						
	BEV			PHEV		FCV	
	<i>Avg EER</i>	<i>SW EER</i>	<i>% diff</i>	<i>Avg EER</i>	<i>SW EER</i>	<i>Avg EER</i>	<i>SW EER</i>
<i>Compact</i>	2.7	2.7	0%	2.6	--	2.5	2.5
<i>Full-size</i>	3.7	3.7	0%	1.8	--	--	--
<i>Mid-size</i>	3.5	4.1	-15%	2.7	--	2.3	2.3
<i>Minivan</i>	--	--	--	3.4	--	--	--
<i>SUV: Small</i>	4.1	5.0	-18%	2.8	--	2.3	2.3
<i>SUV: Standard</i>	4.7	5.0	-5%	2.7	--	--	--

1 Introduction

The proposed *Clean Fuel Regulations* (CFR) require that primary suppliers of gasoline and diesel fuel reduce the carbon intensity of those fuels that they produce or import. Compliance must be achieved by using credits that can be created by the primary supplier or purchased from other credit creators. In addition to actions that reduce the carbon intensity of the fuel across its lifecycle, other credit creating activities include supplying low-carbon fuels and specified end-use fuel switching in transportation. Credits that can be created by end-use fuel switching to electric vehicles are calculated based on energy efficiency ratios (EERs).

EER is a dimensionless ratio that allows comparisons of vehicle efficiency using different fuels. Energy Efficiency Ratio is sometimes called Energy Effectiveness Ratio or Energy Economy Ratio, however all three terms mean the same thing and are all represented as EER. A robust and transparent methodology for calculating EERs within the Canadian context could be beneficial for the deployment of different climate change policies and regulations in the transport sector. NRC was tasked to perform a literature review and to develop a methodology to compute EER values and to calculate these values for several light duty vehicle (LDV) classes (Compact, Mid-size, Full-size, small-SUV, standard-SUV, and Minivan). Several technologies were considered: Plug-in Hybrid Electric Vehicles (PHEVs), Battery Electric Vehicles (BEVs) and hydrogen Fuel Cell Vehicles (FCVs).

EERs were calculated to represent the improvement in efficiency by adopting a clean technology vehicle in a given vehicle class. Three types of EERs were calculated: individual model EERs, simple average and sales-weighted EER for the six classes of LDVs considered. The efficiency of the specific models of the various technologies was computed using publicly available fuel consumption data. The calculated EER values use gasoline powered internal combustion engine vehicles (ICEVs) from the same class as a reference point.

This report is organized as follows: First the scope of work is discussed. Next, the results from the literature review are described. Then, a methodology is presented to compute the EER values. Next, a set of proposed EER values based on the methodology is given. Finally, conclusions are discussed.

2 Scope of Work

2.1 Literature Review

The NRC was tasked to conduct a literature review to determine current practices and methodologies for evaluating EERs in jurisdictions outside of Canada. During this portion of the work sources of data that are required for calculating EERs were identified. The relevant findings from the literature review are summarized in Section 3.

2.2 Develop Energy Efficiency Ratio (EER) Calculation Methodology

A fair, consistent and transparent methodology is needed to calculate the EER values for LDVs in Canada to incentivize fuel switching and reduce GHG to meet Paris agreement targets. The main goal of the project is to develop a bottom up and granular tool to calculate fuel efficiency for different categories of BEVs, PHEVs, and FCVs.

Based on the findings from the literature review the NRC developed and proposed a methodology for calculating EERs for different LDV classes. The methodology considers PHEVs, BEVs, FCVs and ICEVs that are available in Canada using publicly available data. Three EER values were estimated:

- Individual EER value for specific PHEV/BEV/FCV vehicle models
- Average EER for each vehicle class using Canadian sales data
- Sales-weighted average EER for each vehicle class using Canadian-sales data

The EER calculation methodology is detailed in Section 3.5.

2.3 Calculate EERs for LDVs

The proposed methodology was used to calculate EER values for PHEV, BEV, and FCV in the following light duty vehicle classes:

- Compact vehicle (< 2405 L interior volume)
- Mid-size (3115-3400 L interior volume)
- Full-size (> 3400 L interior volume)
- SUV: Small (<2722 kg)
- SUV: Standard (2722-4536 kg)
- Minivan (<3856 kg)

The calculated EER values are presented in Section 5.

2.4 Deliverables

The deliverables for this project consist of:

1. Literature review PowerPoint deck
2. Proposed methodology letter report for approval
3. Calculated EERs PowerPoint deck
4. This final report.

3 Literature Review

3.1 Overview

NRC's Library and Information Management Services conducted an intelligence report. The search emphasized EERs in other jurisdictions, fuel consumption, fleet models, and effects of cold temperatures, fuel efficiency, and data sources. The search returned about 70 journal articles, reports, databases, websites etc. Additional sources were also considered. In total, well over 100 sources were reviewed.

3.1.1 Propulsion Technologies

Several propulsion technologies are currently used for LDVs. Internal combustion engine vehicles (ICEVs) rely on gasoline or diesel as fuel. Hybrid Electric Vehicles (HEVs) have both internal combustion engines and electric motors that are powered by batteries. HEV batteries can't be plugged in to recharge, regenerative braking is used to recharge the batteries. Mild Hybrid Electric Vehicles (MHEVs) are similar to HEVs, but have smaller electric motors and batteries. Plug-in Hybrid Electric Vehicles (PHEVs) also have internal combustion engines and battery-powered motors, but PHEV batteries can be plugged in to recharge. There are three types of PHEVs: series, parallel, and power-split (series-parallel). In series PHEVs, only the motor is attached to the wheel and it is powered by the battery or the gasoline engine. Parallel PHEVs, both the engine and motor are attached to the wheels and can work separately or together. Power-split PHEVs have an electric motor and an engine that are attached to the wheels by a power split device, and the engine and motor can work separately or together. Battery Electric Vehicles (BEVs) have only electric motors. Fuel Cell Vehicles (FCVs) have electric motors that are typically powered by hydrogen fuel cells. More details about PHEV, BEV, and FCV technologies could be found in [1].

3.1.2 Clean Fuel Regulations

The emission of greenhouse gases (GHGs) is a primary cause of climate change. Under the Paris agreement Canada committed to reduce GHG emissions by 2030 to levels that are 30% below 2005 and to achieve net-zero GHG emission by 2050. The Clean Fuel Regulations (CFR) [2] are being developed to meet these commitments. The CFR propose the creation of a credit market to incentivize GHG reduction. Credit creation is done through three credit creating activities: 1) reducing the Carbon Intensity (CI) of fossil fuels, 2) supplying low-carbon fuels 3) end-use fuel switching. The final activity, end-use fuel switching, encourages the adoption of electric vehicles (EVs) and hydrogen powered Fuel Cell Vehicles (FCVs).

For the end-use fuel switching activities, carbon credits are generated by EV charging stations, and FCV fuelling stations. It is proposed in [2] that credits C be calculated by the following equation:

$$C = (R_{ee}CI_{ref} - CI_i)QD \times 10^{-6} \quad (1)$$

Where R_{ee} is the energy efficiency ratio for a particular technology (e.g. BEV, PHEV, and FCV) relative to the displaced technology (e.g. gasoline, diesel);

CI_{ref} is the carbon intensity of the displaced fuel (e.g. gasoline, diesel);

CI_i is the carbon intensity of the compared technology (e.g. electricity ($i=e$), hydrogen ($i=h$));

Q is the amount of electrical energy used to charge EVs (kWh), or the quantity of hydrogen supplied to FCV (kg);

D converts the amount of fuel/energy used to MJ (3.6 MJ/kWh for electricity, or 141.9 MJ/kg for hydrogen).

3.1.3 EERs in other Jurisdictions

In 2009 the California Air Resources Board (CARB) proposed EER values for light duty BEVs, PHEVs, and FCVs [3]. The BEVs considered were the 2000 Nissan Altra, 2003 Toyota RAV4, and the 2006 AC Propulsion eBOX. The 2003 Toyota RAV4 and the 2006 Scion xB were used as the gasoline reference vehicles. The Chevy Volt was considered for PHEVs with the Chevy Cobalt as a gasoline powered reference. EPA fuel economy data was used. The EERs were adjusted by dividing by 1.3 to account for an estimated 30% increase in the fuel economy in gasoline ICEVs from 2009 to 2016. One EER value for both BEVs and PHEVs of 3.0 was suggested at that time from averaging the results from the three BEVs and one PHEV. The 2008 Honda Clarity FCX was used for FCVs, along with the 2009 Honda accord as an ICEV reference vehicle. The EER values were obtained by estimating fuel economy. The adjusted EER of 2.3 was suggested for light duty FCVs.

CARB updated its recommendations in 2011 [4] using US Environmental Protection Agency (EPA) fuel economy data. The EER value for BEVs and PHEVs was suggested to be 3.4 based on the average obtained using the 2011 Chevy Volt and the 2011 Nissan Leaf. The 2011 Chevy Cruze and the 2011 Nissan Versa were used as reference vehicles. The 2011 Honda FCX Clarity and the 2011 Mercedes-Benz F-Cell were considered for FCVs along with the 2011 Honda Accord, 2011 Mercedes SLK350, 2011 Mercedes SLK300, and the 2011 Mercedes C300 as reference vehicles. The recommended EER for FCVs was 2.5. An EER value for light duty BEVs/PHEVs of 3.4 and for light duty FCVs of 2.5 was adopted in California's Clean Fuel Standard (CFS) [4].

The Oregon Department of Environmental Quality's (DEQ) Clean Fuel Program [5] and the British Columbia Ministry of Energy, Mines and Petroleum Resources' Renewable and Low-Carbon Fuel Requirements Regulation (RLCFRR) [6] also adopted the CARB values for BEVs, PHEVs, and FCVs (LDVs and HDVs). These values are summarized in Table 2. The EERs for HDVs are given along with LDVs for reference and comparison.

Table 2: EER values adopted by California [4], Oregon [5] and British Columbia [6].

	Electric to Gasoline (LDV – BEVs/PHEVs)	Electric to Diesel (HDV – BEVs/PHEVs)	Hydrogen to Gasoline (LDV – FCVs)	Hydrogen to Diesel (HDV – FCVs)
California	3.4	5	2.5	1.9
Oregon	3.4	5	2.5	1.9
British Columbia	3.4	5	2.5	1.9

In 2018 CARB [7] used test cycle data from three studies and compared electric vs. diesel buses, drayage trucks, and parcel delivery vans. An equation to estimate EERs based on average duty cycle speed was developed by fitting test cycle data.

$$R_{ee} = 12.34v^{-.309} \tag{2}$$

Where R_{ee} is the Energy Efficiency Ratio (EER);

v is the average speed.

The above relationship is plotted in Figure 1. The curve was obtained by fitting test cycle data for electric trucks and buses [7]. The R-squared value was 0.85. EERs decrease as average speed increases.

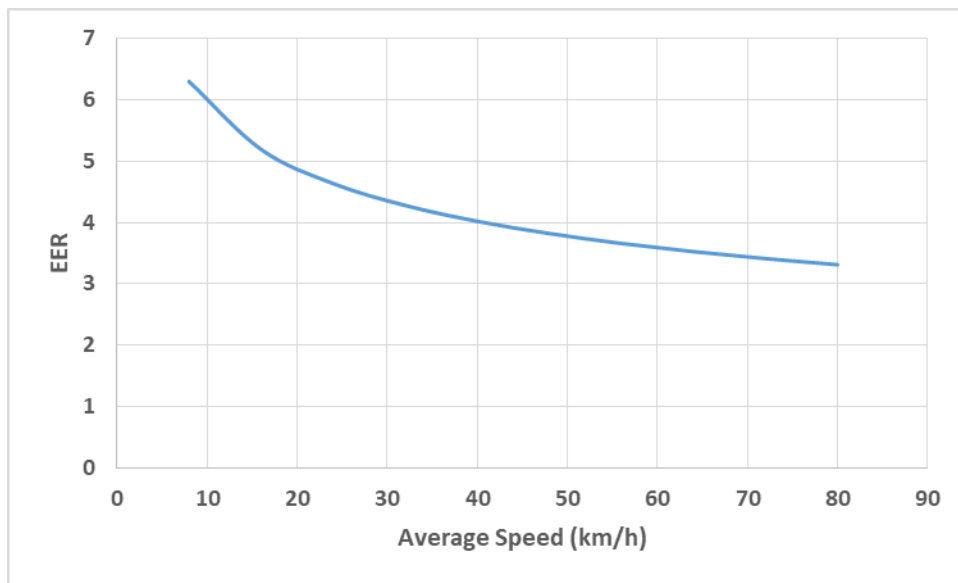


Figure 1: EER vs. average speed, fit to test cycle data for trucks and buses [7].

In-use data was collected during road driving for: electric vs. Compressed Natural Gas (CNG) buses, electric vs. diesel delivery vans, electric vs. diesel airport shuttle, electric vs. diesel yard tractors. The in-use data was compared to Equation 2. In general, there was good agreement, but there was far more scatter with the in-use data compared to the test cycle data. The scatter is expected as the in-use data is subjected to many more random variables: such as traffic, driving conditions, driver behaviour, temperature, etc. Table 3 shows the average EER values for the tests that were reviewed by CARB [7]. We are unaware of any similar study for LDVs or FCVs.

Table 3: EER values obtained from CARB report [7].

Vehicle Type	Fuel Type 1	Fuel Type 2	Data	Average EER
Bus	Electric	Diesel	3 Test Cycles	4.3
Drayage Truck	Electric	Diesel	6 Test Cycles	4.2
Parcel Delivery Van	Electric	Diesel	2 Test Cycles	5.2
Bus	Electric	CNG	In-use Data	8.3
Parcel Delivery Van	Electric	Diesel	In-use Data	6.9
Airport Shuttle Vans	Electric	Diesel	In-use Data	3.8
Yard Tractor	Electric	Diesel	In-use Data	6.2

Conversion of electrical energy or hydrogen fuel cell energy to the gasoline equivalent can use either the higher heating value (HHV) or the lower heating value (LHV). The HHV of gasoline is more appropriate to convert to equivalent gasoline fuel consumption compared to the LHV, which is what is used to compute the equivalent fuel consumption values in the EPA and NRCAN datasets. Since the gasoline powered ICEV uses the gross amount of gasoline, (i.e. HHV), the BEV, PHEV, and FCV use theoretical volumes of gasoline, for consistency, these should be the gross volume (i.e. HHV) instead of the net volume (i.e. LHV). In addition, HHV is used to calculate carbon intensities in RLCFRR with a GHGenius lifecycle model [8]. In addition, HHVs are also used in the CFR and are the basic unit upon which fuel lifecycle analysis is based.

Updated EER LDV values were proposed for BEVs and PHEVs in [9] where the HHV values are used. NRCAN Fuel consumption data was used [10]. The comparisons of the 2011 Nissan Leaf / Versa and 2011 Chevy Volt / Cruze from [7] were updated to reflect the HHV of gasoline. The original CARB value of 3.4 was increased to 3.7 to account for the HHV of gasoline. In addition the comparison was extended to model years 2012-2018. The average EER for the Leaf and Volt by model year is shown in Table 4. The EER ranged between 3.5 and 3.9.

Table 4: EER values for LDV BEVs/PHEVs from comparison of Nissan Leaf/Versa and Chevrolet Volt / Cruze [7] [9].

Year	2011	2012	2013	2014	2015	2016	2017	2018
EER	3.7	3.6	3.5	3.8	3.8	3.9	3.5	3.5

The EER values calculated in the Compact car class are given in Table 5. The EERs for the various BEV/PHEV models ranged from 3.63 to 4.65. The simple average was 4.10 and the sales-weighted average was 3.98. Thus there is only a 3% difference between the simple and sales-weighted averages for the Compact class.

Table 5: Compact class EER values for 2017 BEVs and PHEVs relative to sales-weighted fuel consumption of ICEVs [9].

Vehicle	Chevy Volt	Nissan Leaf	Chevy Bolt	Toyota Prius Prime	Kia Soul BEV	Volkswagen e-Golf	Hyundai Ioniq BEV	Hyundai Ioniq PHEV	Simple Average	Sales-Weighted Average
EER	3.63	3.84	4.10	4.57	3.74	4.15	4.65	4.08	4.10	3.98

The sales-weighted EERs for each class of BEVs/PHEVs is given in Table 6. The lowest EER is for the mid-size SUV class (3.95) and the highest is for the Full-size class (5.04). The average across all classes is 4.14.

Table 6: Sales weighted EERs for BEVs/PHEVs by class [9].

Class	Compact	Mid-size	Full-size	Mid-size SUV	Minivan	BEV/PHEV Average
EER	3.98	4.58	5.04	3.95	4.39	4.14

3.2 Real World Data

Real world data can be an excellent source of fuel consumption information. Data can be collected using GPS or ODB loggers. If a large amount of data is available, using a large enough sample of drivers, and the total coverage is representative of the entire population/fleet, then the data can be very useful in estimating fuel consumption. Individual trip data can have a large variance due to differences in drivers. At present, real world data collection is not a practical way to collect LDV model by model fuel consumption data due to the large number of trips, routes, drivers, different vehicles, etc. needed for each model to obtain a representative sample size.

Real world fuel consumption data has been collected for ICEVs [11], [12] PHEVs and BEVs [13], [12], [14] [15], [16] and FCVs [17]. Data collection can be used to develop duty cycles / drive cycles for computer simulation or dynamometer testing (e.g. [14]). Real world data may be very useful in estimating fuel consumption for other vehicle types, where the number of models is far less, and the typical driving usage is more consistent, thus requiring a lower number of routes to collect data from. Recently data was collected from four ICEV vehicles and one PHEV in Toronto [12].

3.3 Dynamometer Testing

Dynamometer testing attempts to simulate real world driving conditions in a controlled environment to ensure comparability between tests. Fuel consumption ratings are mainly determined by dynamometer testing. Before 2015 a 2-cycle test was used (city and highway). In 2015 the 5-cycle test was introduced by adding three tests: Cold temperature test, Air conditioning test, and the Aggressive driving test. The 5-cycle tests are summarized below:

1. FTP75 (Federal Test Procedure)– simulates city driving
2. HFET (Highway Fuel Economy Test) – simulates highway driving
3. SC03 (Supplemental Federal Test Procedure (SFTP) with Air Conditioning) – simulates effect of air conditioning
4. US06 (SFTP for aggressive city driving) – simulates the effect of high speeds and accelerations
5. FTP20 (Federal Test Procedure cold temperature test) – simulates city driving at low temperatures

The FTP20 test is the same as the FTP75 test, except the FTP20 test is conducted at low temperatures (20°F (-7°C)). Both the FTP20 and FTP75 tests have the drive cycle shown in Figure 2a). The FTP75 test is composed of an FTP-72 (Urban Dynamometer Driving Schedule (UDDS)) test at the beginning and end. An overview of the 5-cycle tests can be found in references [18], [19]. The drive cycles for the EPA tests are shown in Figure 2. Testing requirements for fuel economy ratings are described in [20], [21]. In addition, specific testing procedures are specified for PHEVs [22], BEVs [23], and FCVs [24], [25].



Figure 2: Drive cycles for EPA dynamometer tests: a) FTP test for city driving, b) HFET test for highway driving, c) US06 test for aggressive driving, d) SC03 test for air conditioning.

3.4 Fuel Consumption Models

Various fuel consumption models have been used in literature. They can be very useful and provide key information, especially when real world data or dynamometer testing are not available. Fuel consumption models were considered as a possible source of the data required to calculate EERs.

Fuel consumption depends on many variables including:

- Vehicle characteristics
- Speed
- Acceleration
- Road grade
- Wind
- Temperature
- Road surface
- Driver behaviour

In addition, vehicle models can include several subsystems:

- Driver model
- Control system
- Battery
- Inverter
- Motor
- Engine
- Transmission
- Auxiliary loads.

Each submodel can be equation-based or map-based (e.g. lookup tables) and can connect to other submodels via input and output variables. Fuel consumption models can be classified in several different ways, including:

- Macroscopic, mesoscopic, microscopic [26], [27]
- Physics-based, hybrid, data-driven [28], [29]
- Forward-looking, backward-looking [30].

Macroscopic models use average aggregate parameters to model energy consumption. Microscopic models estimate the second-by-second fuel consumption of individual vehicles. An example of macroscopic models are fleet models discussed in Section 3.5. Individual vehicle models are an example of microscopic models. Mesoscopic models combine features of macroscopic and microscopic models.

Physics-based models (white-box) (e.g. [31]) are developed using the mathematics that describe the physical scenario, while data-driven (black-box) models (e.g. [13]) are based on collected input-output data. Hybrid (grey-box) models use aspects of both physics-based and data-driven models.

Another way to differentiate fuel consumption models is whether they are forward-looking or backward-looking. Forward-looking (dynamic) models start with driver models, and the output is a velocity profile. Backward-looking (quasi-static) models use velocity profiles as inputs, which then are used to determine the forces at the contact patch between the wheel and road. The information is then propagated (backward) through the powertrain to determine torque and energy requirements. Forward-looking models [32], [33] are more computationally expensive, but are more accurate. Backward-looking models [34], [35], [36], [37] are more computationally efficient.

Many different fuel consumption models are available in literature. There are a variety of models developed for ICEVs [38], [34], HEVs/PHEVs [39], [40], BEVs [41], [31], [35], [32], [42] and FCVs [43]. Several good reviews of fuel consumption models are available in [26], [27], [28].

Reference [44] reviewed 125 simulation tools for studying the impacts of electric vehicles on power grids. The authors identified more than 10 simulation tools appropriate for vehicle modeling/analysis.

Several models are available as software tools. Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) [45] is a greenhouse gas emission model that is both forward-looking, and physics-based. It was developed and is used by the EPA. MOtor Vehicle Emission Simulator (MOVES) [46] is a data-

driven model developed by the EPA. Emission FACTor (EMFAC) [47] is another data-driven model that was developed and used by CARB to study emissions. Three more software tools (Autonomie, FastSim, and Malen-Geyer) are described in the following sections.

3.4.1 Autonomie

Autonomie is a forward-looking MATLAB-based software tool developed by the Argonne National Laboratory [33] to evaluate new vehicle technologies. It is able to assess the fuel efficiency / fuel consumption of ICEVs, BEVs, PHEVs, and FCVs. Autonomie is able to create models with a high level of detail (e.g. subsystems, systems). Many publications have used this software and provided validation of its fuel consumption estimates (e.g. [48], [49], [50], [51], [52]). The level of accuracy of fuel consumption is reported to be within 5% [48], [50], [51]. Users outside of the US government must purchase a license.

3.4.2 FastSim

FastSim is another widely used software tool to model fuel efficiency [36], [37] for high-level comparisons. It was developed by the National Renewable Energy Laboratory (NREL) and is free and open source. EXCEL and Python versions are available. FastSim is a backward-looking model and it is simpler to use, but provides less accuracy (5-10%) compared to Autonomie [36]. It has been widely used in the literature and thoroughly validated [53].

FastSim is based on total power demand over time. The total power comes from the sum of traction power and auxiliary power. Traction power is required to overcome vehicles inertia, rotational inertia of wheels, road slope, wind, tire rolling resistance. Auxiliary power is also considered (e.g. HVAC). The required power is then used to estimate power in various components.

FastSim uses generic and simplified models and simplified engine / motor efficiency maps. Therefore, simulations are very fast. It comes with more than 20 vehicle models for ICEVs, BEVs, HEVs, PHEVs, and FCVs. The Python version of FastSim can be combined with large databases of duty-cycles. Temperature effects can be incorporated into the models.

Hamza et al [29] used calibrated FastSim models to study 3 BEVs (Bolt, Leaf, Model-S) and 3 PHEVs (C-Max-Energi, Prius Prime, Volt). Calibration was done using real world data collected by OBD/GPS loggers in California. The authors found that over a large number of trips, over multiple owners the EPA window-sticker values gave reasonable results using default FastSim models. Using the calibrated models improved the accuracy. While FastSim provides good results for a large number of vehicles/trips, a calibration approach has also been developed to improve the accuracy [29].

There is a tool available, called PVC (Plug-in Vehicle Competitiveness) that uses FastSim as a solver [54]. PVC is a tool that is able to run vehicle models on customizable drive cycles or real-world driving. It also has various modules for post processing the results.

3.4.3 Malen-Geyer (MG) Parsimonious Powertrain Models

The MG model was developed to quickly and easily to assess fuel consumption effects of light weighting vehicles. It is simple and uses minimal inputs so it can be used by non-experts. It is based on the required traction force over time, which then determines the engine/motor outputs. It uses full engine / motor maps. Two versions are available, one for ICEVs [55], [56] and another for PHEVs and BEVs [57], [58]. There is no version for FCVs.

3.5 Fleet Models

Fleet models are used to assess the aggregate emissions (or fuel consumption) of the vehicles in a jurisdiction (e.g. country). Fleet models use various inputs to estimate aggregate greenhouse gas emissions or fuel consumption. Several key input parameters are:

- Vehicle sales
- Sales growth
- Vehicle retirement rate
- Annual distance travelled per vehicle
- Vehicle fuel consumption rates

Fleet models are useful to monitor reductions in greenhouse gas emissions and to monitor effects of policies. Light duty vehicle fleet models have been used for the US in [59], [60], [61] and for Norway in [62]. While not directly used in the calculation of EERs, this type of model may be used to monitor the GHG emission reduction in Canada due to cleaner LDV propulsion technologies. This type of model is easy to implement and can be done in a spreadsheet.

Several free fleet modelling tools have been developed: CCAP Guidebook Emissions Calculator [63], ICCT Roadmap [64], [65], FEPIT [66], and FESET [67], [68]. These models differ in the granularity of the input data for computing fleet-wide emissions and the specific policy evaluations they were developed for.

The CCAP Guidebook Emissions Calculator [63] was developed to study effects of various policies on emissions. It is a simplified tool and its calculations are largely based on “rules of thumb” relationships.

ICCT roadmap [64], [65] is another policy evaluation tool for the 2000-2050 time horizon. Fuel consumption input is based on technology type and it includes electric and fuel cell vehicles. GHG and other emissions are assessed as a function of various policies. Several countries and regions are included such as US, EU, China, India, Canada, etc. A good amount of input data can be specified for each mode (e.g. LDV, Bus, etc.).

FEPIT (Fuel Economy Policies Implementation Tool) is another tool for evaluating policy options [66]. Fuel consumption inputs are based on technology type (BEV, PHEV, HEV, and ICEV), however FCV are not included.

FESET is the most recent of the four free tools [67], [68]. Inputs are based on vehicle class (e.g. Compact, Subcompact, etc.). Other modelling assumptions can be adjusted such as: maximum vehicle

age, annual kilometres travelled per vehicle, annual kilometres travelled rebound effect, and a real world adjustment factor. FESET was used to estimate the impact of Mexican GHG standards in [67].

3.6 Cold Climate Research

Fuel consumption is affected by climate in many ways including temperature, precipitation, humidity, and wind. In Canada, where some regions experience very cold winters, low temperatures may produce a large effect on fuel consumption. In general, low temperatures increase fuel consumption in two ways: reduced efficiency of the engine / motor and the increased use of auxiliary power for heating.

The literature contains a large amount of information about the effects of temperature on fuel consumption for ICEVs [69], BEVs/PHEVs [13], [31], [35], [41], [42], [14], [15], [69], [70], [71], and FCVs [43]. Information on effects of cold temperatures on fuel economy can come from real world measurements [13], [14], [71] lab tests [69], [70], or fuel consumption models [31], [35], [41], [42], [43], [15].

Dynamometer testing of BEVs was undertaken by Transport Canada and Environment Canada [70] at temperatures down to -20°C. At -7°C the driving range was found to be about 45% lower compared to 20°C. Losses of 20% and 25% were due to a loss of capacity, and cabin heating respectively.

Fuel consumption of 7 different vehicles (2 ICEVs, 3 HEVs, 1 PHEV, and 1 BEV) were studied by dynamometer testing at temperatures as low as -7°C. Table 7 shows the increase in energy consumption at -7°C for ICEVs, HEVs, PHEVs, and BEVs over four different drive cycles. In general BEVs and PHEVs in charge depleting mode had the largest increase in energy consumption. The cold-start UDDS cycle saw the largest energy consumption increases across all the propulsion technologies.

Table 7: Increase in energy consumption at -7°C compared to 22°C [69]

Cycle	ICEV	HEV	PHEV - Charge Sustaining Mode	PHEV - Charge Depleting Mode	BEV
Cold-Start UDDS	20%	40-70%	60%	100%	100%
Hot-Start UDDS	5-10%	25-70%	20%	95%	90%
HWFET	5%	5-10%	5%	60%	42%
US06	2-3%	2-10%	5%	40%	25%

EVs were modelled at low temperatures [41] and the results indicated that at -5°C the energy consumption of the heating system resulted in 10-32% energy consumption increases for the UDDS, HWFET, and US06 drive cycles. Physics-based modelling of a Nissan Leaf demonstrated significant loss

of energy efficiency at -10°C. The results also showed that efficiency below 0°C is highly dependent on speed [31].

Data was collected from 200 BEVs (741 drivers) over two years in Denmark [13]. The authors found a 34% increase in energy consumption in winter. Real driving data was collected from 197 BEVs in Beijing [14]. Significant increases in electricity consumption at low temperatures (down to -10°C) were observed. Simulations of FCVs in Germany found fuel consumption to be 6% higher in the average winter and 9% higher in the coldest 20% of winter compared to the average spring [43]. A model of a Renault Zoé BEV was used to perform a case study in France that demonstrated an increase of up to 33% as a result of heating in the winter [42]. The effects of low temperatures on medium-duty diesel and electric trucks was studied in Canada [72]. It was found that for the electric trucks energy consumption was almost double at -20°C compared to 20°C.

3.7 Data Sources

In order to compute the EER values fuel consumption and sales data are needed. Fuel consumption data is obtained from NRCan and EPA. Sales data is taken from GoodCarBadCar.net.

3.7.1 Fuel Consumption Data – NRCan

NRCan provides fuel consumption data for ICEVs, BEVs, and PHEVs in three datasets [10]. The three datasets are indicated in Table 8, along with the data fields contained in each dataset. Data is typically determined from either manufacturer supplied 5-cycle test data or 2-cycle test data with adjustment factors [18] [73]. The 2-cycle and 5-cycle tests are described in Section 3.2. Data is available for ICEVs, BEVs, and PHEVs. However, there is no data for FCVs. Vehicle class definitions are given in Table 9 and Table 10. Car classes are determined based on the interior volume and light truck classes depend on gross vehicle weight.

Table 8: Description of NRCan fuel consumption datasets.

MY2021 Fuel Consumption Ratings.csv	ICEVs (including HEVs, mHEVs) – 2021 model year	Year, make, model, class, engine size, cylinders, transmission, fuel type, fuel consumption (city, hwy, combined) (L/100 km), CO ₂ emission, CO ₂ rating, smog rating
MY2012-2021 Battery Electric Vehicles.csv	BEVs – 2012-2021 model years	Year, make, model, class, motor (kW), transmission, fuel type, fuel consumption (city, hwy, combined) (Le/100 km), range, CO ₂ emission, CO ₂ rating, smog rating, recharge time
MY2012-2021 Plug-in Hybrid Electric Vehicles.csv	PHEVs – 2012-2021 model years	Year, make, model, class, motor (kW), engine size, cylinders, transmission, fuel type, fuel consumption (city, hwy, combined) (Le/100 km), range, CO ₂ emission, CO ₂ rating, smog rating, recharge time

Table 9: Car classification based on interior volume [73].

Class	Interior Volume (L)
MiniCompact	< 2405
Subcompact	2405-2830
Compact	2830-3115
Mid-size	3115-3400
Full-size	> 3400
Station Wagon (Small)	< 3680
Station Wagon (Mid-size)	3680 - 4530

Table 10: Light truck classification based on gross vehicle weight [73].

Class	Gross Vehicle Weight (kg)
Pickup Truck (Small)	<2722
Pickup Truck (Standard)	2722-3856
SUV (small)	<2722
SUV (standard)	2722-4536
Minivan	<3856
Van (Cargo)	<3856
Van (Passenger)	<4536
Special Purpose Vehicle	<3856

Using data from [10] (see Table 8), plots of the combined fuel consumption (for ICEVs) or equivalent combined fuel consumption (for BEVs) against several variables have been generated and shown in Figure 3: a) engine size, b) ICEV class, c) motor size, d) BEV class. It can be seen that engine size is a better predictor of combined fuel consumption than class. Motor size appears to be a mildly better predictor of combined fuel consumption compared to class. The correlation between combined fuel consumption and engine size is 0.6751, and between combined fuel consumption and motor size is 0.2125.

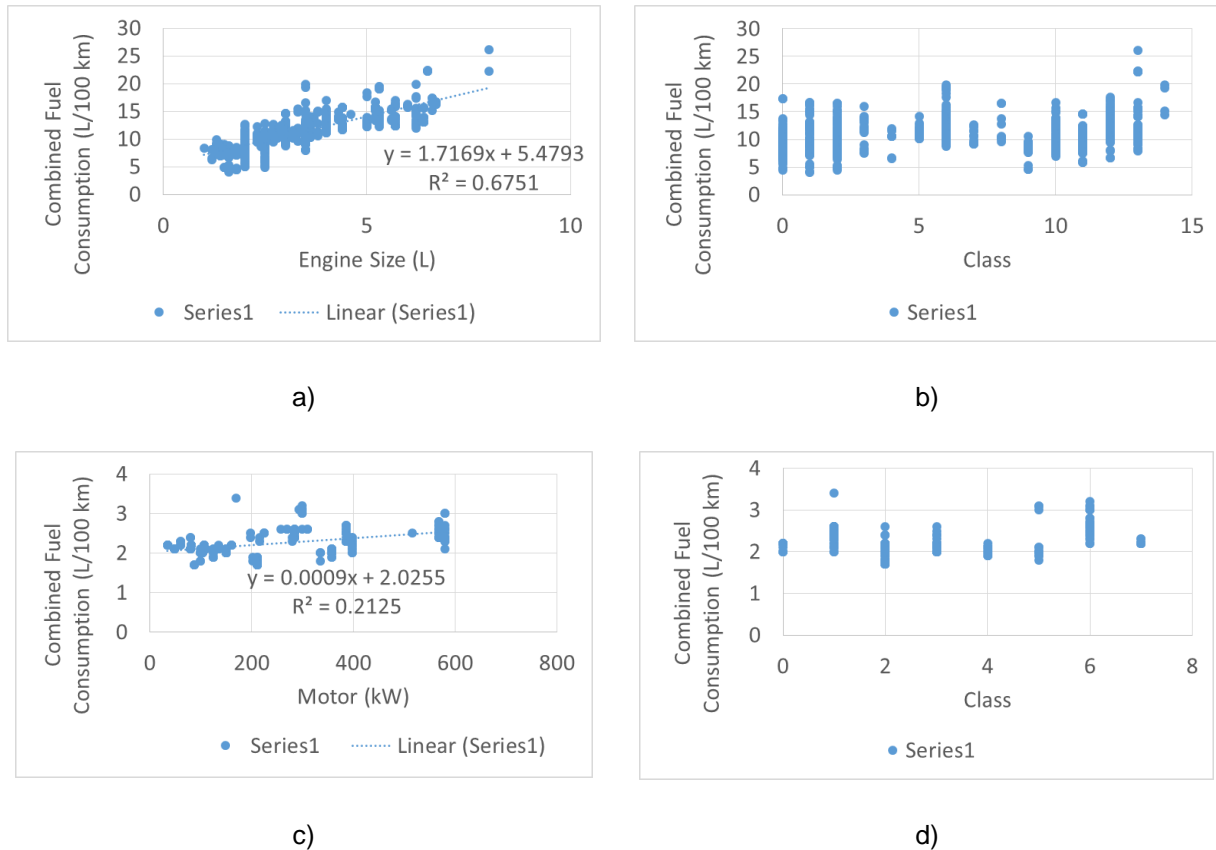


Figure 3: Fuel consumption vs a) ICEV – engine size, b) ICEV – class, c) BEV – motor, d) BEV – class.

3.7.2 Fuel Consumption Data – EPA

The EPA dataset is similar to the NRCAN datasets, however, the EPA dataset has more data fields. HEVs, and MHEVs are distinguished from pure ICEVs. The same vehicle classification system is used by the EPA and NRCAN (Table 10). Fuel consumption data is typically provided by the manufacturer that is based on vehicle specific 5-cycle tests [24], [74], or the derived 5-cycle method using 2-cycle tests and coefficients specified by the EPA [74], [75]. One important aspect of the EPA datasets is that data is available for FCVs.

3.7.3 Sales Data – GoodCarBadCar.net

Canadian auto sales by month and model can be found at GoodCarBadCar.net (GCBC) [76]. This data was used to compute the sales weighted EERs in each vehicle class considered (Compact, Mid-size, Full size, SUV: Small, SUV: Standard, Minivan). Data is available for approximately 300 models and is updated quarterly. In addition, historical aggregate sales data are available. The sales data has limited granularity compared to the fuel consumption data. Sales for PHEV versions of models are not available, and appear to be lumped with ICEV versions of model.

4 Methodology for EER Calculation

The proposed EER calculation methodology is presented in this section. There are four main ways to obtain the fuel/energy consumption values needed to calculate EERs:

1. Real world measurements
2. Laboratory measurements (e.g. test cycles)
3. Physics-based computer simulations (e.g. test cycles or real world route)
4. Data-driven parametric models

Real world data is the most reliable, however it often is not available or incomplete. Laboratory measurements of test cycles are the standard way to estimate fuel consumption of vehicles. If laboratory measurements do not exist, fuel consumption models of the vehicles can be developed to simulate either the test cycles or simulate driving over realistic routes. As described in the previous section, sufficient data exists such that the methodology does not need to rely on any modelling.

4.1 Data Fusion

The NRCan, EPA, and GCBC datasets were fused to create a single dataset that was used to perform the EER calculations and the results are presented in Section 5. In order to do that, the data was cleaned to ensure consistency between vehicle models. The sales data was provided on a different level of granularity than the fuel consumption data. The sales data was slightly more aggregated, and the fuel consumption level provides more granularity on the model level, representing several variations of the same model with different fuel consumption values. PHEV sales data does not seem to be available in the GCBC data, as the PHEV sales data appears to be lumped together with the ICEV versions.

Since vehicles of the same model year are introduced at different times, it makes precisely matching up the sales data and fuel consumption data more challenging. For this reason 2020 sales data was used along with 2021 model year. COVID-19 resulted in 2020 sales being 14% less than 2019 as shown in Table 11. Often the fuel consumption data has duplicate values, which also need to be addressed to match up the data from the two sources. Several model versions were often available in the fuel consumption data. In this case, a single average value for the model was used for EER calculations. Other data gaps exist, such as no minivan BEV or FCV offerings, minimal Compact BEV models, and no Full-size FCV models.

Table 11: Comparison of 2019 and 2020 Canadian LDV sales [76].

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
2019	111,105	123,326	184,150	183,238	202,314	179,013	173,579	181,867	167,436	160,838	144,345	110,238	1,921,449
2020	112,722	138,015	82,649	51,332	119,340	134,906	172,065	161,333	168,711	163,394	132,711	224,382	1,661,560

An overview of the methodology and the data fusion is given in Figure 4. Equivalent fuel consumption data in L/100 km was extracted from the NRCan [10] and EPA [77] datasets. These values were used to calculate the individual model EERs and the class (simple) average EERs. The sales-weighted average EERs used data from NRCan [10], EPA [77], and GCBC [76].

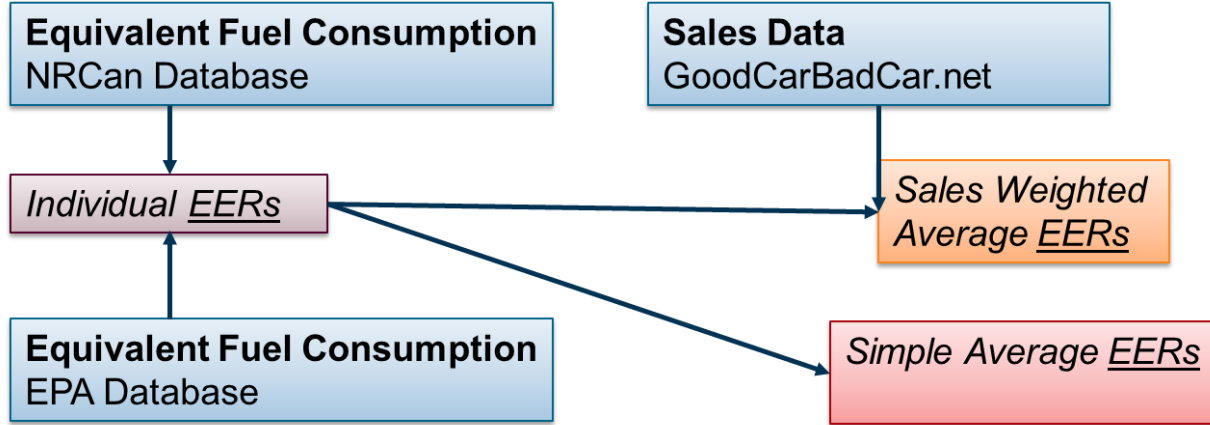


Figure 4: Overview of proposed EER calculation methodology for LDVs.

4.2 EERs for Individual Vehicles

The EERs for individual vehicles are calculated using fuel consumption data from the NRCan/EPA datasets using the following equation:

$$R_{ee}^{i,j} = \alpha \frac{\bar{F}_{icev}^i}{F^j} \quad (3)$$

Where $R_{ee}^{i,j}$ is the EER for vehicle j , from class i ;

F^j is the fuel consumption for vehicle j ;

\bar{F}_{icev}^i is the average (sales-weighted when appropriate) ICEV fuel consumption for vehicle class i ;

$\alpha = \left(\frac{HHV}{LHV}\right)_{gasoline}$ is an adjustment factor to account for the HHV of gasoline.

There are two ways to convert the energy consumption of BEV, PHEV, and FCV into the equivalent gasoline consumption. The first is to use the Lower Heating Value (LHV). This approach is used to calculate the equivalent fuel consumption data from the EPA and NRCan datasets. A second approach is to use the Higher Heating Value (HHV). The HHV includes all combustion energy. It is argued that the HHV provides a more consistent approach [9], and is thus used to recommend EER values for BC. The LHV and HHV of several gasoline types is given in

Table 12. A value of $\alpha = 1.07$ was used in the EER calculations. Hybrid electric vehicles (HEVs) were included with pure ICEVs to calculate \bar{F}_{icev}^i .

Table 12: LHV and HHV of several gasoline types [8].

Gasoline Types	HHV (MJ/kg)	LHV (MJ/kg)	HHV/LHV
Conventional gasoline	46.93	44.01	1.07
Reformulated gasoline	46.93	44.00	1.07
Gasoline used in tractors and engines	46.93	44.00	1.07
New (active) gasoline mix	46.93	44.00	1.07
Methanol/gasoline mix	26.14	23.11	1.13
Ethanol/gasoline mix	45.12	42.18	1.07
Butanol/gasoline mix	45.76	42.82	1.07
Mixed Alcohols/gasoline mix	31.60	28.58	1.11
RBO/Gasoline mix	46.84	43.92	1.07

4.3 Simple Average EERs

EER values were calculated for BEVs, PHEVs, and FCVs in the following classes: Compact, Mid-size, Full-size, SUV: Small, SUV: Standard, and Minivan. The class EERs were calculated in two ways. The first way is by using a simple average EER based on for each technology/class combination. For each class the simple average EER was calculated by:

$$\bar{R}_{ee}^i = \frac{\sum_{j=1}^n R_{ee}^{i,j}}{n} \quad (4)$$

Where \bar{R}_{ee}^i is the average EER for vehicle class i , and n is the number of vehicles in class i .

4.4 Sales-Weighted Average EERs

The EERs are more representative if they are sales-weighted. Therefore, in addition to the simple average EER values, a sales weighted EER value was also calculated for each vehicle class using the following equation:

$$\bar{\bar{R}}_{ee}^i = \frac{\sum_{j=1}^n S^j R_{ee}^{i,j}}{\sum_{j=1}^n S^j} \quad (5)$$

Where $\bar{\bar{R}}_{ee}^i$ is the sales-weighted average EER for vehicle class i ;
 S^j is the total 2020 sales of vehicle j .

4.5 Canadian Climate

The Canadian climate is different than most countries. Many parts of Canada experience long and harsh winters. The low temperatures in the winter almost certainly affect the equivalent fuel consumption for the various technologies. The literature contains a great deal of data on the effects of low temperatures on energy consumption of PHEVs and BEVs. Considerably less data was found for FCVs. In theory approximate adjustments could be made based on published data and population weighted average temperatures (e.g. Canada vs. US). This would require a large effort to accurately capture and ensure that fair adjustments are made across all technologies considered. It would be difficult to ensure consistency with this approach. A second approach could be to adjust the EPA equations [78] to convert the 5-cycle testing data to fuel consumption ratings. More specifically the city fuel consumption rating is determined by weighting the results of the standard temperature and cold temperature tests. This weighting could be adjusted to reflect the Canadian climate, but this would require considerable effort to ensure the validity of the adjustments. A more detailed study of climatic effects on EERs is required in order to adjust EERs to more accurately capture the true efficiency effects in the Canadian climate. Therefore, no adjustments have been made to account for the Canadian climate. The effect of the Canadian climate on LDV EERs is an area that requires further research. This would provide more accurate relative comparisons between the technologies as they are expected to perform in the Canadian climate.

5 Canadian LDV EERs

The EERs for LDVs are presented in this section. The EERs are calculated according to the approach presented in Section 4. The data used to compute these values are included in Appendix A. After removing vehicles that were out of scope, and merging redundant data, the final data set contains over 200 ICEV vehicles. Table 13 shows the average fuel consumption for ICEVs for several LDV classes. The simple average values range from 9.2 (Compact) to 13.2 (SUV: Standard) and the sales-weighted values range from 7.5 (Mid-size) to 12.1 (SUV: Standard).

Table 13: Average fuel consumption for ICEVs by vehicle class.

Class	Simple Average Fuel Consumption (L / 100 km)	Sales-Weighted Average Fuel Consumption (L / 100 km)
Compact	9.2	8.1
Full-size	11.2	7.6
Mid-size	9.9	7.5
Minivan	10.1	9.2
SUV: Small	9.6	9.0
SUV: Standard	13.2	12.1

Fifteen BEVs are included in the final dataset.

Table 14 shows the average equivalent fuel consumption, the simple average EER, and the sales weighted EER values for various classes of BEVs. The simple average EER values range from 2.7 (Compact) to 4.7 (SUV: Standard). The sales weighted EER values vary from 2.7 (Compact) to 5.0 (SUV: Small and SUV: Standard). There were no BEVs in the Minivan class. The final column compares the EERs with results from [9]. The sales weighted EERs calculated in this report are lower compared to Compact, Full-size and Mid-size, while both SUV classes have higher EER values compared to [9]. It should be noted that the EER values from [9] are for BEVs and PHEVs, and the cars in each category are not identical. Nevertheless, comparing those serves as a good guide.

Table 14: Proposed EER values for BEVs by vehicle class.

Class	Simple Average Equivalent Fuel Consumption (Le / 100 km)	Sales-Weighted Average Equivalent Fuel Consumption (Le / 100 km)	Simple Average EER	Sales-Weighted Average EER	EER values from [9]*
Compact	3.2	3.2	2.7	2.7	4.0
Full-size	2.2	2.2	3.7	3.7	5.0
Mid-size	2.3	2.0	3.5	4.1	4.6
Minivan	--	--	--	--	4.4
SUV: Small	2.3	1.9	4.1	5.0	4.0
SUV: Standard	2.7	2.6	4.7	5.0	4.0

* vehicle classes are not identical and PHEV and BEV values are grouped together

The final dataset includes 38 PHEVs. The average EER value for each class of PHEVs is shown in Table 15. The average EER values range from 1.8 (Full-size) to 3.4 (Minivan). Sales data was not available for PHEVs, therefore there are no sales-weighted averages for PHEVs. The EER values in this report are lower than [9] for all classes. Several reasons for the differences are different model years, not identical classes, and lumping PHEVs together.

Table 15: Proposed EER values for PHEVs by vehicle class.

Class	Simple Average Equivalent Fuel Consumption (Le / 100 km)	Simple Average EER	EER values from [9]*
Compact	3.3	2.6	4.0
Full-size	4.5	1.8	5.0
Mid-size	3.0	2.7	4.6
Minivan	2.9	3.4	4.4
SUV: Small	3.4	2.8	4.0
SUV: Standard	4.8	2.7	4.0

* Vehicle classes are not identical and PHEV and BEV values are grouped together

Three FCVs are in the final dataset, and the EER values are summarized in

Table 16. The three FCVs are in the Compact, Mid-size and SUV: Small classes. The sales-weighted and simple averages are the same in this case and range from 2.3 to 2.5.

Table 16: Proposed EER values for FCVs by vehicle class.

Class	Simple and Sales-Weighted Average Equivalent Fuel Consumption (Le / 100 km)	Simple Average EER	Sales-Weighted Average EER
Compact	3.5	2.5	2.5
Full-size	--	--	--
Mid-size	3.5	2.3	2.3
Minivan	--	--	--
SUV: Small	4.2	2.3	2.3
SUV: Standard	--	--	--

The calculated EER values is summarized in Table 17. Each row corresponds to a vehicle class. EER values are given for three technologies. There are three columns for BEVs, the average EER (Avg EER) and the sales weighted average EER (SW EER), and the percent difference between the two for comparison. Both EER values are the same for Compact and Full-size. The other EERs differed by between 5% and 18%, with the simple average always being lower. The simple average BEV EERs ranged from 2.7 to 4.7, while the sales weighted EERs ranged from 2.7 to 5.0. PHEVs have only simple average EERs. The simple average EERs for PHEVs ranges from 1.8 to 3.4. For FCVs the simple average and sales weighted average EERs are the same. The EERs value range from 2.3 to 2.5 for FCVs.

Table 17: Summary of EER values by technology and vehicle class.

Class	Technology						
	BEV			PHEV		FCV	
	Avg EER	SW EER	% diff	Avg EER	SW EER	Avg EER	SW EER
<i>Compact</i>	2.7	2.7	0%	2.6	--	2.5	2.5
<i>Full-size</i>	3.7	3.7	0%	1.8	--	--	--
<i>Mid-size</i>	3.5	4.1	-15%	2.7	--	2.3	2.3
<i>Minivan</i>	--	--	--	3.4	--	--	--
<i>SUV: Small</i>	4.1	5.0	-18%	2.8	--	2.3	2.3
<i>SUV: Standard</i>	4.7	5.0	-5%	2.7	--	--	--

The range of EER values is provided in Table 18 along with the average values for each technology to allow comparison to values adopted by other jurisdictions. The BEV and FCV values are in excellent agreement overall. The PHEV EERs presented in this report are lower than the other references in general. One reason may be that in the other sources PHEVs and BEVs were grouped together.

Table 18: Basic statistics of calculated EER Values (simple average and sales-weighted) for each technology compared with EER values adopted by California [4], Oregon [5] and British Columbia [6], and values from [9].

Technology	Minimum of Avg and SW EERs	Maximum of Avg and SW EERs	Simple Average of Class Avg and SW EERs	Overall Sales-Weighted Average EER	Adopted Values [4] [5] [6]	Simple Average Values [9]
BEV	2.7	5.0	3.9	4.2	3.4	4.1
PHEV	1.8	3.4	2.7	--	3.4	4.1
FCV	2.3	2.5	2.4	2.4	2.5	--

6 Conclusions

Several different propulsion technologies are available for LDVs in Canada with ICEVs being the most common with the most complete data sets. Combustion engines are typically fueled by either gasoline or diesel while battery electric vehicles (BEVs) are powered by rechargeable batteries. In the case of Plug-in Hybrids (PHEVs), both battery and gasoline are used for propulsion, and the battery can be recharged by plugging the vehicle in. Lastly, Hydrogen Fuel Cell Vehicles are powered by onboard hydrogen fuel cells that drives an electric motor.

The Clean Fuel Regulations (CFR) require primary suppliers of liquid fossil fuels to gradually reduce the carbon intensity of fuels. Compliance with the regulations can be accomplished in two ways: the demonstration of the reduction target or by purchasing credits from other credit creators. In addition to the reduction of carbon intensity, other credit creating activities include supplying low-carbon fuels and end-use fuel switching. Credits for the second way (fuel switching to electric/hydrogen) are calculated based on Energy Efficiency Ratios (EERs). An EER is a dimensionless ratio that allows comparisons of vehicle efficiency using different fuels. It is a measure of the reduction of carbon emissions from the combustion of liquid fuels such as gasoline and diesel.

There were three key tasks associated with this project. The first task was to perform a literature review that focused on fuel consumption models, lab testing, real world testing, effects of cold weather on fuel consumption, and data sources. Over 100 sources were consulted for the literature review to determine the state of the art on EER calculations, fuel consumption modelling and testing, climatic effects, and data availability.

The second task was to develop a methodology to calculate EER values for several LDV classes informed by the literature review. A methodology has been proposed to evaluate the EER value for technology/vehicle class combinations. A transparent and consistent methodology was described using publicly available data to determine EER values for LDVs.

The third task was to create a dataset and calculate the EERs for several technologies and several LDV classes. Data from three main sources (NRCan, EPA, and GoodCarBadCar.net) was fused to create a dataset of sales and fuel consumption data for several classes of LDVs. The data was also cleaned to remove duplicate entries for each model.

The proposed EERs for individual LDV classes were presented in Section 5. In general, they agree well with the aggregate values adopted by BC, California, and Oregon, in addition to other values found in literature. These EER values could be continuously or periodically updated and made publicly available for reference. Future research studying the impacts of the Canadian climate and operating environment on LDV EERs is recommended to improve accuracy and provide a more realistic picture of how the various propulsion technologies will perform in the Canadian climate.

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Appendix A – Fuel Consumption and Sales Datasets

Table A1: Fuel consumption and sales data for ICEVs, HEVs, and mHEVs.

Year	Make	Model	Vehicle Class	Comb (L/100 km)	2020 Sales
2021	Acura	ILX	Compact	8.6	924
2021	Acura	TLX	Compact	9.8	9169
2021	Audi	A4	Compact	8.55	2229
2021	Audi	S4 Sedan Quattro	Compact	10.1	-
2021	BMW	228i xDrive Gran Coupe	Compact	8.8	1357
2021	BMW	330i xDrive Sedan	Compact	8.3	3873
2021	BMW	M235i xDrive Gran Coupe	Compact	9.2	-
2021	BMW	M340i xDrive Sedan	Compact	9.2	-
2021	Cadillac	CT4	Compact	9.57	355
2021	Genesis	G70	Compact	11	1173
2021	Honda	Insight Touring	Compact	4.9	496
2021	Hyundai	Veloster N	Compact	10	1051
2021	Kia	Rio	Compact	6.85	4493
2021	Lexus	IS	Compact	10.37	1328
2021	Lexus	UX 250h	Compact	6.27	1904
2021	Mazda	CX-3	Compact	7.93	6445
2021	Mazda	Mazda3	Compact	8.02	7394
2021	Mercedes-Benz	Mercedes-Benz AMG GT	Compact	12.63	299
2021	Mercedes-Benz	Mercedes-Benz C-Class	Compact	10.7	3970
2021	Mercedes-Benz	Mercedes-Benz CLA-Class	Compact	9.5	1085
2021	Mercedes-Benz	Mercedes-Benz E / CLS-Class	Compact	9.85	898.5
2021	Mercedes-Benz	Mercedes-Benz S-Class	Compact	12.2	553
2021	Mitsubishi	Mirage	Compact	6.35	1230
2021	Nissan	Versa	Compact	7.2	125
2021	Rolls-Royce	Dawn	Compact	17.4	-
2021	Subaru	WRX	Compact	11.57	3687
2021	Toyota	C-HR	Compact	8.2	7135
2021	Toyota	Corolla	Compact	6.9	37156
2021	Volkswagen	Golf	Compact	8.08	13113
2021	Volkswagen	Jetta	Compact	7.73	10552
2021	Volvo	S60	Compact	9.07	1321
2021	Audi	A8	Full-size	12.35	127
2021	Audi	S8 Sedan Quattro	Full-size	14.5	-
2021	BMW	540i xDrive Sedan	Full-size	9.1	874
2021	BMW	750i xDrive Sedan	Full-size	12	94
2021	BMW	750Li xDrive Sedan	Full-size	12	94

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Year	Make	Model	Vehicle Class	Comb (L/100 km)	2020 Sales
2021	BMW	Alpina B7 xDrive	Full-size	12	-
2021	BMW	M760i xDrive Sedan	Full-size	15.1	-
2021	Chrysler	300	Full-size	11.2	413
2021	Dodge	Charger	Full-size	12.57	1659
2021	Genesis	G80	Full-size	10.35	189
2021	Genesis	G90 AWD	Full-size	12.8	59
2021	Honda	Accord	Full-size	6.86	7844
2021	Honda	Civic Hatchback	Full-size	7.9	25402.5
2021	Hyundai	IONIQ	Full-size	4.1	5117
2021	Hyundai	Sonata	Full-size	7.3	3585
2021	Kia	K5	Full-size	8.45	373
2021	Maserati	Quattroporte	Full-size	13.33	31
2021	Porsche	Panamera	Full-size	12.58	268
2021	Rolls-Royce	Ghost	Full-size	16.7	-
2021	Rolls-Royce	Phantom	Full-size	16.3	-
2021	Subaru	Legacy	Full-size	8.3	1360
2021	Volkswagen	Arteon 4MOTION	Full-size	9.8	352
2021	Alfa Romeo	Giulia	Mid-size	9.83	187
2021	Audi	A5 Sportback 45 TFSI Quattro	Mid-size	8.8	2507
2021	Audi	A6	Mid-Size	9.45	527
2021	Audi	A7 Sportback 55 TFSI Quattro	Mid-size	9.7	382
2021	Audi	RS 5 Sportback Quattro	Mid-size	11.4	-
2021	Audi	RS 7 Sportback Quattro	Mid-size	13.5	-
2021	Audi	S5 Sportback Quattro	Mid-size	10.1	-
2021	Audi	S6 Sedan Quattro	Mid-size	10.9	-
2021	Audi	S7 Sportback Quattro	Mid-size	10.9	-
2021	Bentley	Flying Spur	Mid-size	14.85	-
2021	BMW	530i xDrive Sedan	Mid-size	8.9	437
2021	BMW	M5 Sedan	Mid-size	13.8	-
2021	BMW	M5 Competition	Mid-size	13.8	-
2021	BMW	M550i xDrive Sedan	Mid-size	11.7	-
2021	BMW	M8 Gran Coupe	Mid-size	13.8	-
2021	BMW	M8 Gran Coupe Competition	Mid-size	13.8	-
2021	BMW	M850i xDrive Gran Coupe	Mid-size	12	-
2021	Cadillac	CT5	Mid-size	10.37	851
2021	Chevrolet	Malibu	Mid-size	8.3	3287
2021	Dodge	Challenger	Mid-size	13.39	1368
2021	Honda	Civic Sedan	Mid-size	7.2	25402.5
2021	Honda	Insight EX	Mid-size	4.9	496
2021	Hyundai	Elantra	Mid-size	6.58	25006
2021	Hyundai	Venue	Mid-size	7.65	10740

Year	Make	Model	Vehicle Class	Comb (L/100 km)	2020 Sales
2021	Infiniti	Q50	Mid-size	10.95	1040
2021	Kia	Forte	Mid-size	7.43	16715
2021	Kia	Stinger AWD	Mid-size	11.8	1289
2021	Lexus	ES	Mid-size	8.05	1550
2021	Lexus	LS	Mid-size	10.15	22
2021	Lexus	UX 200	Mid-size	7.2	952
2021	Maserati	Ghibli	Mid-size	12.83	94
2021	Mazda	Mazda3	Mid-size	8.23	7394
2021	Mazda	Mazda6	Mid-size	8.45	1137
2021	Mercedes-Benz	Mercedes-Benz E / CLS-Class	Mid-size	10.23	898.5
2021	MINI	Cooper	Mid-size	8.8	2739
2021	MINI	Countryman	Mid-size	8.97	1637
2021	Nissan	Altima	Mid-size	8	1418
2021	Nissan	Kicks	Mid-size	7.2	14009
2021	Nissan	Maxima	Mid-size	9.9	851
2021	Nissan	Sentra	Mid-size	7.63	6806
2021	Rolls-Royce	Wraith	Mid-size	16.5	-
2021	Subaru	Impreza	Mid-size	8.25	6643
2021	Toyota	Avalon	Mid-size	8.95	235
2021	Toyota	Camry	Mid-size	7.69	11631
2021	Toyota	Prius	Mid-size	4.65	6417
2021	Volkswagen	Passat	Mid-size	8.3	1754
2021	Volvo	S90 T6 AWD	Mid-size	9.6	137
2021	Chrysler	Grand Caravan	Minivan	10.6	26
2021	Chrysler	Pacifica	Minivan	11.3	2461
2021	Honda	Odyssey	Minivan	10.6	6026
2021	Kia	Sedona	Minivan	11.5	4228
2021	Toyota	Sienna	Minivan	6.6	8821
2021	Alfa Romeo	Stelvio	SUV: Small	10.4	487
2021	BMW	X1 xDrive28i	SUV: Small	9.1	2384
2021	BMW	X2	SUV: Small	8.85	790
2021	BMW	X3	SUV: Small	12.15	5660
2021	BMW	X4	SUV: Small	12.15	1241
2021	Buick	Encore	SUV: Small	8.88	6650
2021	Buick	Encore GX	SUV: Small	8	5045
2021	Buick	Envision	SUV: Small	9.2	2122
2021	Cadillac	XT4	SUV: Small	9.3	3498
2021	Cadillac	XT5	SUV: Small	10.27	4217
2021	Cadillac	XT6	SUV: Small	10.85	1491
2021	Chevrolet	Blazer	SUV: Small	10.14	3861
2021	Chevrolet	Equinox	SUV: Small	8.6	12502

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Year	Make	Model	Vehicle Class	Comb (L/100 km)	2020 Sales
2021	Chevrolet	Trailblazer	SUV: Small	8	2487
2021	Chevrolet	Trax	SUV: Small	8.8	3887
2021	FIAT	500X AWD	SUV: Small	9.1	35
2021	Ford	Bronco	SUV: Small	12.34	195
2021	Ford	EcoSport	SUV: Small	8.8	4866
2021	Ford	Edge	SUV: Small	10.25	13213
2021	Ford	Escape	SUV: Small	7.4	23747
2021	GMC	Terrain	SUV: Small	8.8	9848
2021	Honda	CR-V	SUV: Small	7.9	50135
2021	Honda	Passport AWD	SUV: Small	11.3	3017
2021	Honda	Pilot AWD	SUV: Small	11	9340
2021	Hyundai	Kona	SUV: Small	8.37	31733
2021	Hyundai	Santa Fe	SUV: Small	9.1	15721
2021	Hyundai	Tucson	SUV: Small	9.77	28444
2021	Infiniti	QX50 AWD	SUV: Small	9.7	1897
2021	Jeep	Cherokee	SUV: Small	10.18	9544
2021	Jeep	Compass	SUV: Small	9.4	5222
2021	Jeep	Renegade	SUV: Small	9.42	362
2021	Jeep	Wrangler	SUV: Small	11.22	22707
2021	Kia	Seltos	SUV: Small	8.2	16881
2021	Kia	Sorento	SUV: Small	9.8	11821
2021	Kia	Sportage	SUV: Small	10	11789
2021	Kia	Telluride AWD	SUV: Small	11.3	3474
2021	Lexus	NX	SUV: Small	9.03	6954
2021	Lexus	RX 350	SUV: Small	10.95	4614
2021	Lincoln	Corsair	SUV: Small	9.85	-
2021	Lincoln	Nautilus	SUV: Small	10.83	1753
2021	Mazda	CX-30	SUV: Small	8.64	10945
2021	Mazda	CX-5	SUV: Small	9.08	30583
2021	Mazda	CX-9 4WD	SUV: Small	10.5	4887
2021	Mercedes-Benz	Mercedes-Benz GLC/GLK-Class	SUV: Small	11.6	6983
2021	Mitsubishi	RVR	SUV: Small	9.13	-
2021	Nissan	Rogue	SUV: Small	8.2	25998
2021	Porsche	Macan	SUV: Small	11.88	2283
2021	Subaru	Crosstrek	SUV: Small	8.43	22161
2021	Subaru	Forester AWD	SUV: Small	8.2	13134
2021	Subaru	Outback	SUV: Small	8.65	12556
2021	Toyota	Highlander	SUV: Small	10.3	8228.5
2021	Toyota	RAV4	SUV: Small	7.77	67977
2021	Toyota	Venza AWD	SUV: Small	6.1	1403
2021	Volkswagen	Atlas	SUV: Small	11.37	9370

Year	Make	Model	Vehicle Class	Comb (L/100 km)	2020 Sales
2021	Volkswagen	Tiguan	SUV: Small	9.65	14240
2021	Volvo	XC40	SUV: Small	9.35	2254
2021	Volvo	XC60	SUV: Small	10.1	3148
2021	Acura	RDX	SUV: Small	10.1	9169
2021	Audi	Q3	SUV: Small	9.75	5949
2021	Audi	Q5	SUV: Small	9.3	8048
2021	Mercedes-Benz	Mercedes-Benz GLA-Class	SUV: Small	9.5	1759
2021	Mercedes-Benz	Mercedes-Benz GLB	SUV: Small	9.65	1776
2021	Aston Martin	DBX V8	SUV: Standard	15.2	-
2021	Audi	Q8 55 TFSI Quattro	SUV: Standard	12	1323
2021	Audi	RS Q8 Quattro	SUV: Standard	15.4	-
2021	Audi	SQ7 Quattro	SUV: Standard	13.9	-
2021	Audi	SQ8 Quattro	SUV: Standard	13.9	-
2021	Bentley	Bentayga	SUV: Standard	14.75	-
2021	BMW	X5	SUV: Standard	13.63	4785
2021	BMW	X6	SUV: Standard	13.63	1028
2021	BMW	X7	SUV: Standard	12.45	1345
2021	Buick	Enclave	SUV: Standard	11.5	1773
2021	Cadillac	Escalade	SUV: Standard	15.05	1755
2021	Chevrolet	Suburban	SUV: Standard	14.27	1045
2021	Chevrolet	Tahoe	SUV: Standard	14.08	2625
2021	Chevrolet	Traverse	SUV: Standard	11.45	5319
2021	Dodge	Durango	SUV: Standard	14.6	5667
2021	Ford	Expedition	SUV: Standard	12.85	4408
2021	Ford	Explorer	SUV: Standard	10.68	15283
2021	Genesis	GV80	SUV: Standard	11.15	296
2021	GMC	Acadia	SUV: Standard	10.18	3109
2021	GMC	Yukon	SUV: Standard	14.08	3725
2021	GMC	Yukon XL	SUV: Standard	14.27	498
2021	Hyundai	Palisade	SUV: Standard	10.8	8636
2021	Infiniti	QX80 4WD	SUV: Standard	15.1	741
2021	Jeep	Grand Cherokee	SUV: Standard	14.02	16967
2021	Lamborghini	Urus	SUV: Standard	16.9	-
2021	Lexus	GX 460	SUV: Standard	14.5	523
2021	Lexus	LX 570	SUV: Standard	16.9	921
2021	Lexus	RX 450h	SUV: Standard	8	4614
2021	Lincoln	Aviator AWD	SUV: Standard	11.9	1941
2021	Lincoln	Navigator 4X4	SUV: Standard	13.5	1207
2021	Maserati	Levante	SUV: Standard	14.1	227
2021	Mercedes-Benz	Mercedes-Benz G-Class	SUV: Standard	15.14	925
2021	Mercedes-Benz	Mercedes-Benz GL/GLS-Class	SUV: Standard	13.4	2256

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Year	Make	Model	Vehicle Class	Comb (L/100 km)	2020 Sales
2021	Mercedes-Benz	Mercedes-Benz GLE-Class	SUV: Standard	12.36	6150
2021	Nissan	Armada 4WD	SUV: Standard	15.4	358
2021	Porsche	Cayenne	SUV: Standard	12.98	3150
2021	Subaru	Ascent AWD	SUV: Standard	10.4	3626
2021	Toyota	4Runner	SUV: Standard	13.8	7821
2021	Toyota	Highlander	SUV: Standard	6.7	8228.5
2021	Toyota	Sequoia 4WD	SUV: Standard	16.4	455
2021	Volkswagen	Atlas 4MOTION	SUV: Standard	12.9	9370
2021	Volvo	XC90	SUV: Standard	10.3	2389
2021	Audi	Q7	SUV: Standard	11.65	2248

Table A2: Fuel consumption and sales data for BEVs

Year	Make	Model	Vehicle Class	Combined Fuel Consumption (L/100 km)	2020 Sales
2021	Porsche	Taycan	Compact	3.15	421
2021	Tesla	Model S	Full-size	2.2	961
2021	Hyundai	IONIQ Electric	Mid-size	1.8	-
2021	Nissan	LEAF	Mid-size	2.17	1535
2021	Polestar	2	Mid-size	2.6	-
2021	Porsche	Taycan Cross Turismo	Mid-size	3.18	421
2021	Tesla	Model 3	Mid-size	1.83	6151
2021	BMW	i3	Subcompact	2.1	168
2021	MINI	Cooper SE 3 Door	Subcompact	2.2	-
2021	Hyundai	Kona Electric	SUV: Small	2	-
2021	Tesla	Model Y	SUV: Small	1.93	1100
2021	Volkswagen	ID.4 Pro	SUV: Small	2.45	-
2021	Volvo	XC40 Recharge	SUV: Small	3	-
2021	Audi	e-Tron	SUV: Standard	3.05	548
2021	Tesla	Model X	SUV: Standard	2.43	1275

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Table A3: Fuel consumption and sales data for PHEVs.

Year	Make	Model	Vehicle Class	Combined Fuel Consumption (L/100 km)
2021	BMW	330e	Compact	3.1
2021	Volvo	S60 T8 AWD	Compact	3.2
2021	BMW	330e xDrive	Compact	3.5
2021	BMW	745Le xDrive	Full-size	4.2
2021	Audi	A8 L Sedan 60 TFSI e Quattro	Full-size	4.4
2021	Porsche	Panamera 4 E-Hybrid	Full-size	4.5
2021	Porsche	Panamera Turbo S E-Hybrid	Full-size	4.9
2021	Toyota	Prius Prime	Mid-size	1.8
2021	Hyundai	IONIQ Plug-in Hybrid	Mid-size	2
2021	Honda	Clarity Plug-in Hybrid	Mid-size	2.1
2021	Audi	A7 Sportback 55 TFSI e Quattro	Mid-size	3.3
2021	BMW	530e	Mid-size	3.4
2021	Volvo	S90 T8 AWD	Mid-size	3.6
2021	MINI	Cooper SE Countryman ALL4	Mid-size	3.2
2021	BMW	530e xDrive	Mid-size	3.8
2021	Chrysler	Pacifica Hybrid	Minivan	2.9
2021	Karma	GS-6 (21" Wheels)	Subcompact	3.4
2021	Karma	Revero GT (21" Wheels)	Subcompact	3.4
2021	Karma	GS-6 (22" Wheels)	Subcompact	3.8
2021	Karma	Revero GT (22" Wheels)	Subcompact	3.8
2021	Ford	Escape Plug-in Hybrid	SUV: Small	2.2
2021	Toyota	RAV4 Prime	SUV: Small	2.5
2021	Subaru	Crosstrek Hybrid AWD	SUV: Small	2.6
2021	Lincoln	Corsair Grand Touring	SUV: Small	3
2021	Mitsubishi	Outlander PHEV AWD	SUV: Small	3.2
2021	Jeep	Wrangler 4xe	SUV: Small	4.8
2021	Audi	Q5 55 TFSI e Quattro	SUV: Small	3.1
2021	BMW	X3 xDrive30e	SUV: Small	3.9
2021	Volvo	XC60 T8 AWD	SUV: Small	4
2021	Lincoln	Aviator Grand Touring	SUV: Standard	4.2
2021	BMW	X5 xDrive45e	SUV: Standard	4.4
2021	Volvo	XC90 T8 AWD	SUV: Standard	4
2021	Porsche	Cayenne E-Hybrid	SUV: Standard	5.1
2021	Bentley	Bentayga Hybrid	SUV: Standard	5.1
2021	Porsche	Cayenne Turbo S E-Hybrid	SUV: Standard	5.6

Table A4: Fuel consumption and sales data for FCVs.

Year	Make	Model	Vehicle Class	Combined Fuel Consumption (L/100 km)	2020 Sales
2021	Toyota	Mirai	Compact	3.68	12
2021	Toyota	Mirai XLE	Compact	3.31	12
2021	Honda	Clarity	Mid-size	3.51	749
2021	Hyundai	Nexo	SUV: Small	4.36	4
2021	Hyundai	Nexo Blue	SUV: Small	4.06	4

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