Modelling a Zero-Emission Vehicle Standard and Subsidies in Canada's Light-Duty Vehicle Sector (2023-2035)

Prepared for
Environmental Defence and Équiterre

By the Sustainable Transportation Action Research Team (START)

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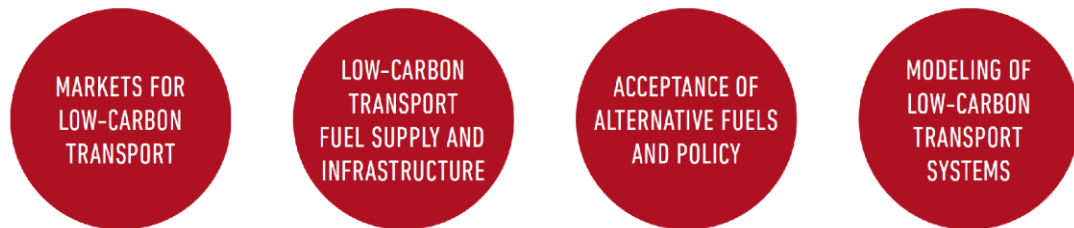*Chandan Bhardwaj, Researcher*

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About the Sustainable Transportation Action Research Team (START)

We take an interdisciplinary approach to low-carbon transportation solutions, integrating relevant insights from quantitative and qualitative research methods, such as statistical analyses, energy-economy modeling, consumer and citizen surveys, stakeholder interviews, media analysis and policy analysis. Our current research focus centers around four main themes:

MARKETS FOR LOW-CARBON TRANSPORT

LOW-CARBON TRANSPORT FUEL SUPPLY AND INFRASTRUCTURE

ACCEPTANCE OF ALTERNATIVE FUELS AND POLICY

MODELING OF LOW-CARBON TRANSPORT SYSTEMS

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Environmental Defence is a leading Canadian environmental advocacy organization that works with government, industry and individuals to defend clean water, a safe climate and healthy communities. For over 35 years, Environmental Defence has worked at the municipal, provincial and federal level to safeguard our freshwater, create livable communities, decrease Canadians' exposure to toxic chemicals, end plastic pollution, tackle climate change and build a clean economy.

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Équiterre seeks to make the necessary collective transitions toward an equitable and environmentally sound future more tangible, accessible, and inspiring. Since 1993, Équiterre has been helping to find solutions, transform social norms, and encourage ambitious public policies through research, support, education, mobilization, and awareness-building initiatives. This progress is helping to establish new principles for how we feed ourselves, how we get around, and how we produce and consume, that are designed for our communities, respectful of our ecosystems, in line with social justice, and of course, low in carbon.

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Background

Canada has set ambitious goals for the sale of zero-emissions vehicles (ZEVs), aiming for ZEVs to make up 20% of annual light-duty vehicle (LDV) sales by 2026, 60% by 2030, and 100% by 2035.[a] Although these goals are described as "mandatory" targets, it is not yet clear what policy mechanism or mixes will be used to induce such an increase in sales. Based on international evidence, achieving a 100% ZEV sales goal will certainly require an additional strong policy or policy mix relative to the current climate policies in place in Canada.[1]

In this study, we explore two policy pathways for Canada to meet its ZEV sales goals, which all extend the "baseline" climate policies already in place. These are:

1. **A stringent ZEV sales standard** that requires automakers to achieve light-duty ZEV market shares that align with the stated sales goals, with a strong financial penalty charged for non-compliance ($20,000[b] per credit).
2. **A subsidy-based strategy** that triples the amount of national purchase subsidies to $15,000 for battery electric vehicles (and most plug-in hybrid vehicles), which we model as shorter-term (lasting until 2026), medium-term (until 2030), and longer-term (2035) versions.

We also consider the combination of the ZEV standard and longer-term subsidy. This report compares these policy scenarios in terms of ZEV sales, greenhouse gas (GHG) emissions reductions, automaker profits, vehicle markups and prices, and government financial expenditure.

Method

We use the AUtomaker-consumer Model (AUM) to simulate the impacts of these policies on Canada's LDV sector from 2023 to 2035. AUM is unique in that it simulates interactions between behaviorally-realistic consumers and an aggregate profit maximizing automaker. Consumer preferences are based on empirical survey data collected from Canadian car-buyers, and preferences can change with increased exposure to ZEVs. AUM endogenously represents multi-year foresight for a profit-maximizing automaker, including decisions about: (i) increasing ZEV model variety, (ii) intra-firm cross-price subsidies, and (iii) investing in R&D to reduce future ZEV costs. Parameters are drawn from the literature, and model performance is calibrated with current sales and with forecasts from other models and studies. We represent uncertainty by conducting uncertainty analysis with "optimistic" and "pessimistic" parameters relative to ZEVs, and also produce uncertainty ranges for key model outputs.

Key findings

1. ZEV sales: we find that the current ("baseline") policies in place in Canada (as of Summer 2022) are not nearly strong enough to meet ZEV sales goals in 2030 or 2035 (Fig. ES1). All

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[a] Government of Canada (2022), Canada's Zero-Emission Vehicle (ZEV) sales targets, https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles/canada-s-zero-emission-vehicle-zev-sales-targets

[b] All dollars in this report are Canadian unless stated otherwise.

three subsidy-based scenarios increase 2035 new market share to 44-69%. However, the 2030 and 2035 ZEV sales goals are not met even under optimistic conditions, even with a $15,000 national subsidy in place until 2035. In contrast, the ZEV standard induces 95-100% market share in 2035, achieving or coming very close to achieving Canada's sales goals.

Figure ES1: National ZEV market share in new vehicle sales (individual policies, median case)
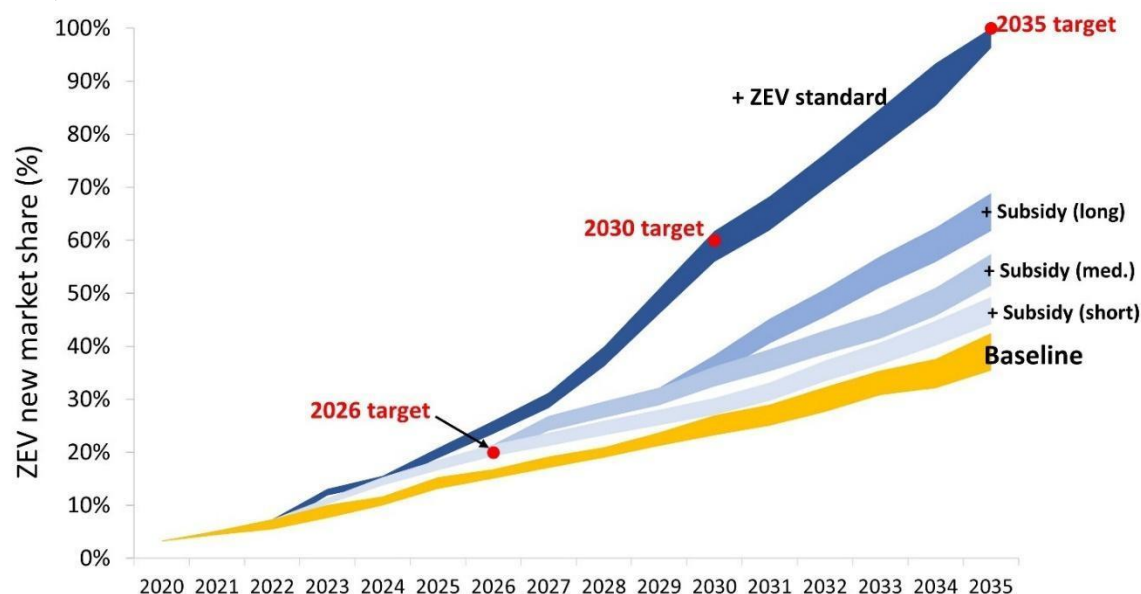
2. GHG emissions: the modeled ZEV standard would result in a 58-62% decline in annual light-duty transportation GHG emissions from 2022 levels by 2035 (Fig. ES2). Tripling national purchase incentives all the way to 2035 only reduces annual emissions by 42-45%. In terms of cumulative emissions compared to the baseline (2023-2035), the subsidy scenarios induce GHG reductions of 11-19 Mt in the short-term subsidy, 35-41 Mt in the medium-term subsidy, and 39-50 Mt in the longer-term subsidy. The ZEV standard induces GHG reductions that are three to ten times greater, at 123-137 Mt.

3. Automaker profits: in all scenarios, automaker profits in 2035 are higher than in 2022. Compared to the baseline, cumulative profits (2023-2035) are increased by the subsidy scenarios by 1-4%, while the ZEV standard decreases cumulative profits by 7.5%. Though, in the ZEV standard, automaker profits still increase by 15% higher from 2022 to 2035. The combined standard and subsidy scenario reduces cumulative profits by only 4.2%—effectively softening the impact of the ZEV standard.

4. Vehicle markups[c]: under all scenarios, ZEV markups are gradually increased from 2023 to 2035 as the technology becomes more mature. Compared to the average markup of 25% in the baseline from 2023-2035, the ZEV standard induces firms to lower the average ZEV markup to 18%. In contrast, the subsidy scenarios lead to an increase in average ZEV markups to 27%

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[c] We broadly define the vehicle "Markup" as the percentage difference between the vehicle sales prices and the manufacturing costs. We do not distinguish between what portion of this is taken to automakers, dealerships, or other firms.

during that period (due to partial automaker and dealership capture of the subsidy). For conventional internal combustion engine (ICE) vehicles, the ZEV standard leads to higher markups, while the subsidies lead to marginally lower ICE markups.

Figure ES2: National GHG emissions from light-duty vehicles (neutral ZEV standard plus policy mixes, uncertainty range includes pessimistic and optimistic parameters)
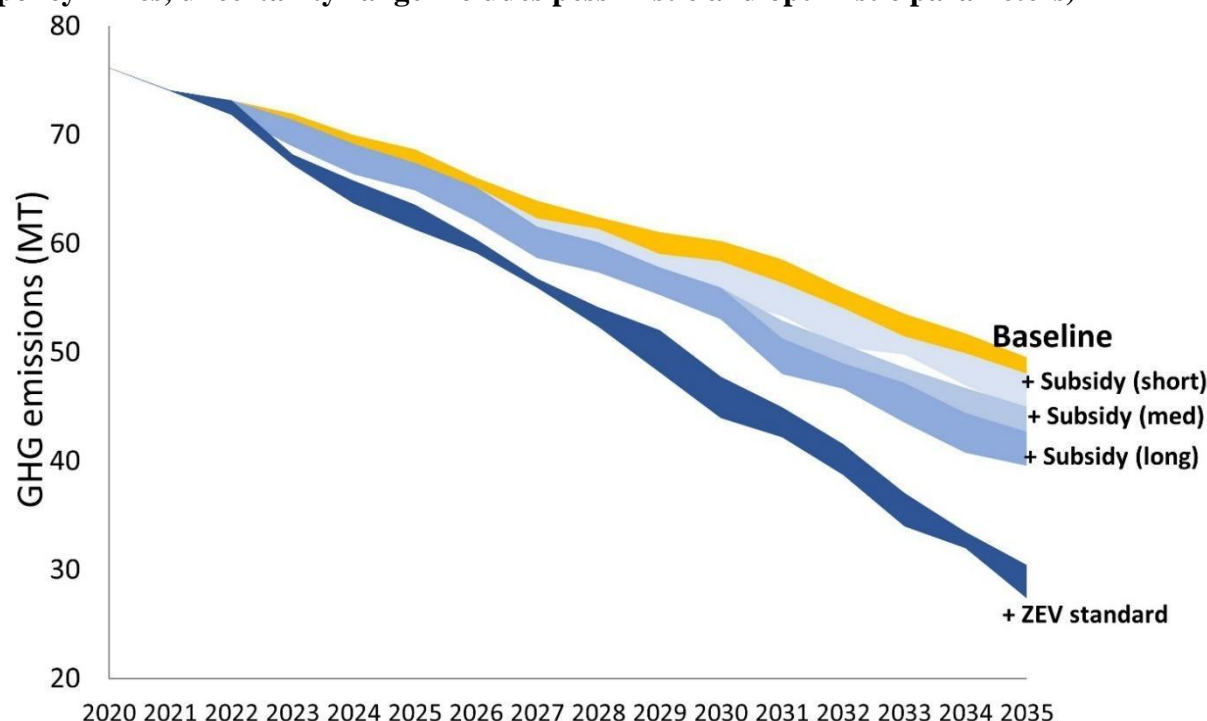
5. ZEV sales prices: all policy scenarios induce a reduction in the sales price of ZEVs compared to the baseline. The ZEV standard leads to an average drop of about $7200 from 2023-2035, or a 22% reduction from the baseline. The subsidy scenarios induce an average ZEV price reduction of about 30% while the subsidy is in place, though this price advantage largely disappears once the national subsidy is removed.

6. ICE sales prices: the ZEV standard induces automakers to increase the average price of ICE vehicles by 6% from the baseline scenario (from 2023-2035) to help them achieve the required sales targets. In contrast, the subsidy scenarios induce an average reduction of ICE prices of 1-8% (reductions of $200 to $2300 per vehicle), with the larger price reductions for the long-term subsidy.

7. Automaker investment in ZEV Research & Development (R&D)[d] : Automaker investment in ZEV-related R&D is not substantially impacted by the subsidy scenarios. However, the ZEV standard induces an initial increase of annual R&D spending of about 180%, and more than doubles the cumulative ZEV R&D spending from 2023-2035 compared to the baseline.

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[d] R&D investment includes any investment costs (including capital and labour) that can contribute to lower ZEV costs nationally over time, apart from the global exogenous decline in battery and other component costs

8. Government subsidy expenditure: in each scenario, the subsidy portion of the policy package requires billions of dollars in government expenditure in the modeled time horizon (2023-2035, undiscounted). The baseline and ZEV standard scenarios include current purchase incentives, which are simulated to require about $2.5 billion in expenditure. When the national subsidy is tripled, government expenditure increases to $8 billion for the shorter-term subsidy, $24 billion for the medium-term subsidy, and $54 billion for the longer-term subsidy. Combining a ZEV standard and longer-term subsidy requires over $80 billion in government expenditure, due mainly to the high level of ZEV sales (which are multiplied by the subsidy per vehicle). In the subsidy scenarios, the cost of government expenditure is over $32,000 per additional ZEV sold, and over $450 per additional tonne of CO_2e reduced (both values are consistent with published studies).

9. Automaker subsidy capture (incidence)[e] : In the three subsidy-based scenarios, automakers (and potentially other auto industries) are found to capture 13-18% of the value of the purchase subsidies in the median case (or $1 billion to $10 billion over the 2023-2035 time period), with higher capture occurring for the longer-term subsidy.

Policy recommendations

Of the two policy pathways we evaluate, **the ZEV standard offers a number of advantages compared to a large and sustained subsidy-based approach**. In particular, compared to the subsidy scenarios we examine, the ZEV standard can:

- Achieve (or come close to achieving) ZEV sales goals for 2026, 2030 and 2035;
- Achieve more substantial GHG reductions by 2035;
- Induce a reduction in average ZEV sales prices by about one-fifth;
- Induce a doubling in domestic automaker investment in ZEV-related R&D;
- Still allow an overall increase in automaker profits from 2022 to 2035; and
- Reduce government expenditure on subsidies by an order of magnitude.

In contrast, the subsidy scenarios offer more benefits to automakers, including increases in automaker profits due to partial capture of the subsidy value. Also, when the large subsidies are in place, there is a larger decrease in average ZEV sales prices of around 30%, though this could potentially come with a slight decrease in ICE prices as well.

Finally, there could be a benefit to combining the ZEV standard and some duration of the stronger subsidies. Our modeling suggests that this policy combination can reduce the impact of a ZEV standard on profits, while still achieving: the ZEV sales goals, substantial GHG emissions reductions, and increased R&D investment. However, this policy combination will increase the requirements for government expenditure—potentially up to tens of billions of dollars if kept until 2035.

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[e] We define incidence as the share (%) of subsidy pass through to buyers, following Muehlegger and Rapson (2018). The automakers capture the remaining subsidy. For example, 82% pass through to buyers implies an 18% subsidy capture by automakers.

1. Introduction

Canada has set ambitious goals for the sale of zero-emissions vehicles (ZEVs), aiming for ZEVs to make up 20% of annual light-duty vehicle (LDV) sales by 2026, 60% by 2030, and 100% by 2035.[f] Although these goals are described as "mandatory" targets, it is not yet clear what policy mechanism or mixes will be used induce such an increase in sales. Based on international evidence, achieving a 100% ZEV sales goal will certainly require an additional strong policy or policy mix relative to the current policies in place.[1]

A large motivator is to achieve the nation's goals to reduce emissions by 40-45% by 2030 (relative to 2005 levels) and net zero by 2050.[g]   The transportation sector represents about 28-30% of greenhouse gas (GHG) emissions in Canada.[2] Between 2005 and 2019, GHG emissions in Canada's transport sector grew by 14% (the fastest growing IPCC sector), and by 18% in the road transport sector.[3]

Modeling research of Canada's LDV sector indicates that stronger policy is needed to push 2030 ZEV sales to a 30% market share goal—even with the subsidies, pricing mechanisms, and regulations currently in place.[4,5] Achieving a 100% ZEV sales goal by 2035 will certainly require the addition of a particularly strong policy or policy mix.[1]

This report considers two policy pathways for Canada to meet its 2030 and 2035 ZEV sales goals. First is a ZEV sales standard, which requires automakers to sell a minimum market share of ZEVs, with financial penalties for non-compliance.[6] Since first being introduced in California in 1990, ZEV standards have also been introduced into several other US states, as well as British Columbia, Quebec, and China. In the last year, the North American ZEV standards have been updated to require 100% sales by 2035, including the British Columbia and Quebec versions. We explore the potential of a national level ZEV standard with a similar trajectory of requirements.

Second is ZEV purchase subsidies, which are in place in nations and sub-national regions throughout the world.[7,8] ZEV purchase subsidies typically range from $2,500 to $20,000 per vehicle, where larger incentives can indeed boost ZEV sales.[4,9-11] However, such incentives need to be in places for a long duration to have sustained GHG impacts (if not accompanied by strong policy), potentially for a decade or longer. Purchase incentives are generally found to be a less cost-effective than other policies, and due to free-ridership effects can require up to $30,000–$35,000 of government expenditure per additional ZEV sold.[10,12] Further, automakers tend to adjust their pricing so that they capture up to 10-20% of the purchase subsidy (known in economics as the subsidy "incidence"),[13] though in some cases this capture rate can be lower.[14,15]

In short, the two pathways can have very different impacts on ZEV sales, GHG emissions, automakers, and government expenditure—all of which are explored in this report. Next, we

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[f] Government of Canada (2022), Canada's Zero-Emission Vehicle (ZEV) sales targets, https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles/canada-s-zero-emission-vehicle-zev-sales-targets

[g] Canada has not identified specific decarbonization goals for the light-duty vehicle sector. For our analysis, we assume the 2030 GHG reduction goal is proportional for this sector (also a reduction of 40% relative to 2005 levels).

further details our research objectives, the simulation model (AUM), our policy scenarios, and results.

2. Research objectives

Our primary goal is to simulate the impacts of a ZEV standard and ZEV purchase subsidies in Canada, in terms of ZEV sales, GHG emissions, government expenditure, and automaker impacts. Specifically, we simulate the status quo climate policies in Canada as the "baseline" (current carbon pricing, ZEV purchase subsidies, and regulations), and to this explore three different types of additions, starting in 2023:

1. A "stringent" ZEV sales standard, requiring ZEV sales of 20% by 2026, 60% by 2030, and 100% by 2035.
2. Three durations of a "subsidy-based strategy", where national iZEV purchase incentives are tripled ($15,000 for BEVs and $7,500 for PHEVs). We model versions that end the national incentives in 2026, 2030, or 2035.
3. The combination of the same stringent ZEV sales standard (in #1 above) and the longer-term of the subsidy-based strategy.

We report on the key outputs for each policy scenario, including:

- Canada's ZEV new market share for light-duty vehicles (2020-2035)
- GHG emissions from Canada's stock of light-duty vehicles (2020-2035)
- Automaker profits (2020-2035)
- Markups and sales prices of ZEVs and ICE vehicles (2020-2035)
- Induced ZEV investment from automakers (2020-2035)
- Direct government expenditure on incentives (2023-2035), as well as:
  - Fiscal cost in dollars of subsidy expenditure per additional ZEV sold
  - Fiscal cost in dollars of subsidy expenditure per additional ton of GHG reduced,
- Incidence of subsidies, which is the percentage captured by consumers versus automakers (2020-2035)

For each simulation we also conduct a form of uncertainty analysis, where each policy scenario is run with "median" parameter assumptions, as well as "pessimistic" and "optimistic" parameter values.

3. The AUtomaker-consumer Model (AUM)

We use the AUtomaker-consumer Model (AUM) to simulate the impacts of these policies on Canada's light-duty vehicle sector. AUM is unique in that it simulates interactions between behaviorally-realistic consumers and an aggregate profit maximizing automaker, as depicted in Fig. 1.[5] Specifically, the automaker (or vehicle supply) model and the consumer model interact by passing data in each one-year time period. AUM endogenously represents multi-year

foresight for the automaker, including decisions about: (i) increasing ZEV model variety, (ii) intra-firm cross-price subsidies, and (iii) investing in R&D to reduce future ZEV costs.

Figure 1: Structure of the AUM technology adoption model
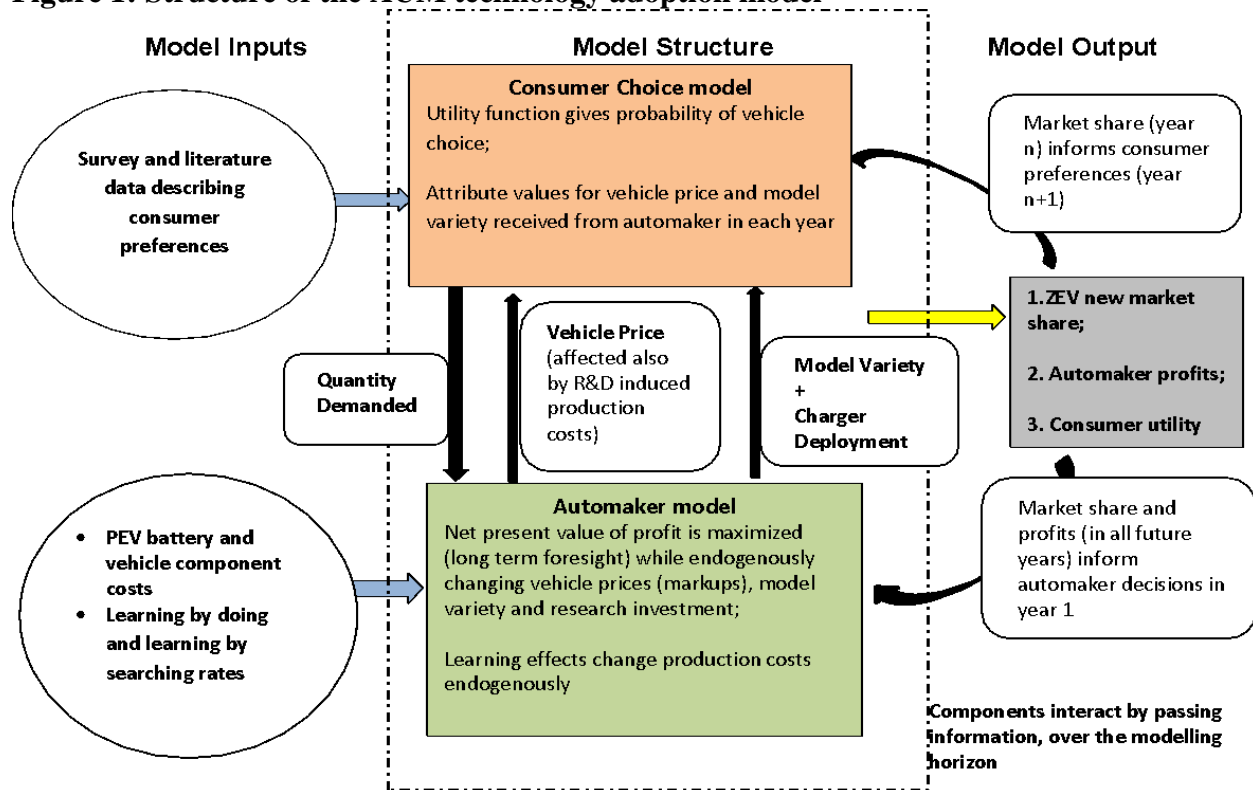
As examples, the automaker model selects prices and number of vehicle models available, while in each year consumers demand a certain number of vehicles. For a given year, the main outputs of the model are ZEV sales (as a proportion of light-duty vehicle sales), automaker profits and consumer utility. The model can thus be used to analyse a variety of policies based on their effect on outcome indicators such as ZEV market share, automaker profits, and consumer utility. AUM also accounts the stock of vehicles, and estimates well-to-wheels GHG emissions for the fleet of light-duty vehicles.

In the following subsections, we summarize the demand-side and supply side models, the method used to calculate policy costs, and the validation process used to calibrate AUM.

3.1 Demand-side model

The consumer choice model simulates annual light-duty vehicle sales and market share in Canada from 2020 to 2035. Total vehicle sales are in turn affected by prices generated by the automaker model using own-price elasticities (that is, for every 1% increase in average vehicle purchase price, what is the percentage decrease in vehicle sales). In each year, consumers choose

from the available options to satisfy the demand for new vehicles, generating annual light-duty vehicle sales which are split between conventional ICE vehicles, hybrid vehicles, PHEVs, and BEVs.

The consumer model is a nested discrete choice model (Fig. 2). At the first level of the nest, a consumer makes a choice between different vehicle classes (compact, sedan, SUV, pick-up truck). At the second level, the consumer chooses between different vehicle drivetrain technologies (conventional ICE vehicles, hybrid, PHEV, and BEV) within each class. Though, as detailed next, the availability of a given drivetrain in a given year is determined by the automaker model. For certain drivetrains (PHEV and BEV), the third level of the nested discrete choice hierarchy is a choice of vehicle electric-driving range. PHEVs can include electric ranges of 60, 100 and 120 km, and BEVs can include ranges of 100, 180, 240, 320 and 480 km.

Figure 2: Nesting of consumer choices in AUM
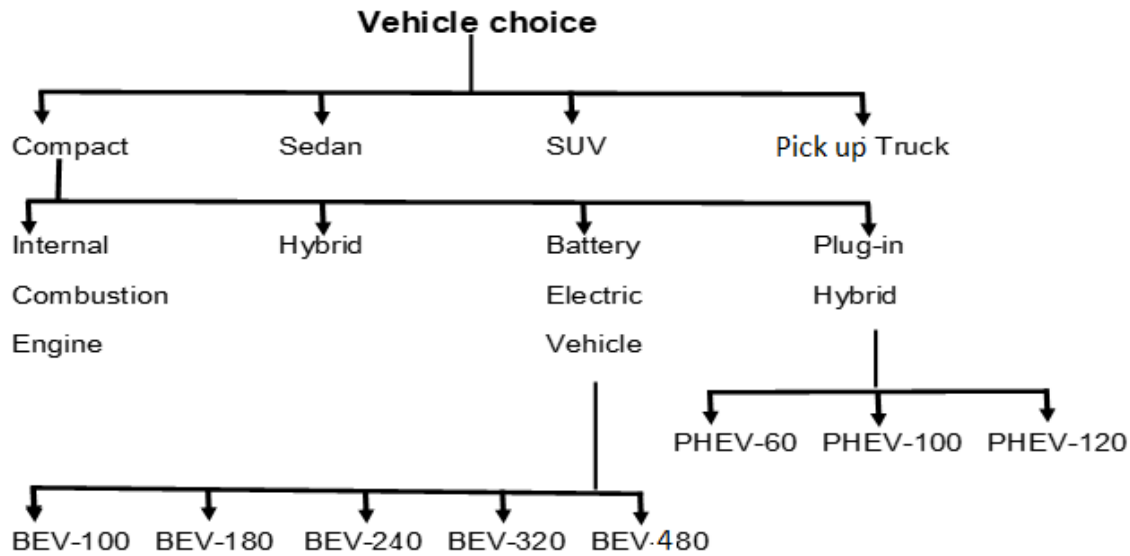
Consumers choose the vehicle technology which provides the highest utility, based on a utility function. The utility function indicates the utility a consumer derives from the purchase of vehicle technology *i*, and draws largely from the LAVE-Trans model, as follows:[16]

$$U_i = ASC + \beta_{PP}X_{PP} + \beta_{FC}X_{FC} + \beta_{CA}X_{CA} + \beta_R X_R + \beta_{MV}X_{MV} \quad (1)$$

Where the utility of the consumer is influenced by the vehicle technology's purchase price (PP), fuel costs (FC), electric driving range (R), recharging access (CA), and vehicle model variety (MV). Purchase price indicates the vehicle price (vehicle cost + markup added by automaker) as observed by consumers. Fuel cost indicates the annual running costs of a vehicle. Electric driving range indicates the number of kilometres a vehicle can run without needing recharging. Recharging access is the percentage of filling/recharging stations with electric charging, relative to gasoline stations.[17]

Model variety, expressed as natural logarithm of the percentage of models relative to conventional vehicles, captures the idea that availability of models for battery electric and plug-in hybrid electric vehicles (n_j) is limited, affecting consumers' purchase decisions. The value of model variety is given by the logarithm of the ratio nj/N, where N is the number of models of conventional vehicles.[18] For example, in 2020, only about 28 models for plug-in electric vehicles existed in Canada, in comparison to about 300 for conventional vehicles. Thus, for the year 2020, model variety for plug-in electric vehicles is about 10% relative to conventional vehicles.

The ASC, or Alternative Specific Constant, contains the component of utility not captured by other attributes.

The probability $P_{i|j}$ (indicating the market share, MS) of a consumer choosing a technology 'i' is then given by:

$$P_{i|j}(MS) = \frac{e^{U_i}}{\sum_{k=1}^{n} e^{U_k}} \qquad (2a)$$

The probability that technology i will be selected is the product of the probability of choosing a nest j (where j represents a nest at Level 1 or 2 in Fig. 2) and the probability of choosing i, given that a choice will be made from the nest j: $Pij = Pi|j*Pj$.

We use empirical data sources to inform our consumer utility equation. ASC base-year values and the base year weights for the other attributes in equation (1) are empirically derived largely from the Canadian Plug-in Electric Vehicle Study (CPEVS) and Canadian Zero Emissions Vehicle Study (CZEVS) survey data,[19,20] and in part from international literature.[21-23] Consumers' base year willingness to pay for the different attributes are listed in Table 1. The CPEVS included a three-part survey completed by a representative sample of 1754 new vehicle buying Canadian households in 2013 while the CZEVS 2017 survey is essentially an updated version of the previous study. Both studies contain responses to survey questions on ZEV awareness, weekly driving distance, vehicle class for the next planned vehicle purchase, and preferences for vehicle attributes. The latent-class choice model was used to identify five heterogeneous consumer classes in the sample for both surveys, discussed further below.

Table 1: List of attributes and the corresponding estimated willingness to pay (WTP) values of their coefficients

Attribute	WTP ($)			Range in literature ($)	Sources with comparable values of WTP
	ZEV - Enthusiasts (15%)	Mainstream (50%)	ZEV Resistors (35%)		
Purchase price	-	-	-		Axsen et al. [19]; Kormos et al. [20]
Fuel cost (per $1,000 a year in fuel savings)	6000	4000	2000	(1000,7000)	Brand et al.[21]
Driving range (per km increase in electric range)	30	15	15	(20,200)	Ferguson et al. [23]; Dimitripoulos et al. [22]
Model variety (natural log of per 1% increase in number of PEV models, relative to CVs)	3500	3500	3500	(0,10000)	Brand et al.[21]; Green [18]
Recharging access (per 1% increase in recharging stations)	550	550	550	(100,1000)	Ferguson et al. [23]; Hackbarth and Madlener [17]
ASC in 2020 **PHEV** **BEV** **HEV** **ASC in 2035** **(optimistic, median, pessimistic)** **PHEV** **BEV** **HEV**	 5000 8000 3000 (2275, 2030, 1800) (4020, 2750, 2150) (0,0,0)	 -10000 -15000 -3000 (0, -2400, -3050) (0, -3850, -5535) (0, 0, 0)	 -30000 -40000 - 5000 (0, -8954, -15k) (0, -13500, - 20,000) (0, 0, 0)	(-50000, 8000)	Axsen et al. [19]; Kormos et al. [20]

To simulate dynamics in consumer preferences, the ASC parameter changes endogenously over time as a function of cumulative vehicle sales of drivetrain technology k (either conventional, battery electric or plug-in hybrid electric) as follows:

$$ASC_{tk} = ASC_{ok} \times e^{b(cumulative\ sales\ of\ drivetrain\ technology\ k\ in\ Canada)} \qquad (3)$$

Where the ASC_{ok} represents the value of the ASC parameter at time $t=0$ for technology k; b = constant (as used in National Research Council).[16]

While the data for all attributes in equation (1) for the first modelling year is exogenously specified, the data for each attribute for the remaining years are determined either exogenously (for fuel prices and charger availability, Table 2) or endogenously as inputs from the automaker model. As shown in Fig. 1, vehicle purchase price and model variety values are endogenously taken from the automaker model. However, model variety also has an exogenous component, to represent the global increase in the number of models. The exogenous assumptions regarding model variety are also listed in Table 2.

To represent heterogeneity in consumer preferences, we include three consumer segments: "ZEV Enthusiasts" (15% of consumers), "Mainstream" (50%) and "Resistors" (35%). These proportional splits are exogenous and constant across the modelling horizon. Dynamics in preferences are instead represented via changes in the ASC for a given segment. As noted, these three classes are drawn from the five consumer classes identified in past Canada-based consumer research. [9,10] First, "ZEV Enthusiasts" have a high positive valuation (negative risk aversion) for electric vehicles. The "Resistors" segment favour conventional vehicles and have a high negative valuation for electric vehicles. The third segment, "Mainstream", represents consumers with an initial, moderate bias against ZEVs.

Table 2: Optimistic, Median and Pessimistic values for key model parameters

	2020	2022	2023	2030			2035			
Parameters	Values			Median	Optimistic	Pessimistic	Median	Optimistic	Pessimistic	Source
Model variety (relative to CVs)	10%	20%	25%	70%	90%	40%	100%	100%	60%	Authors' judgement,
Recharging access (%, relative to gas stations)	10%	15%	20%	70%	90%	50%	100%	100%	60%	Authors' judgement
Gasoline price ($CDN/litre, exclusive of carbon price)	0.83	1.78	1.6	1.02	1.70	0.70	0.65	1.70	0.51	National Energy Board [24], US EIA [25], IEA [26]; Knuemo [27] EIA citation
Battery costs (CDN$/kWh in 2020)	230	180	180	110	70	130	70	40	100	Lutsey et al.[28]; IEA[29]; Bloomberg[30]
Consumer own-price elasticity for vehicle purchase (2020-2035)	-0.6	-0.6	-0.6	-0.6	-0.3	-1	-0.6	-0.3	-1	Fouquet [31]; Holmgren [32]
Consumer elasticity for travel demand (2020-2035)	-0.2	-0.2	-0.2	-0.2	-0.15	-0.25	-0.2	-0.15	-0.25	Small and van Dender [33]
Automaker rate of learning (%) (2020-2035)	8	8	8	8	10	6	8	10	6	Weiss et al. [34]; Barreto and Kypreos [35]
Automaker discount rate (%) (2020-2035)	10	10	10	10	8	15	10	8	15	Jagannathan et al. [36]
Vehicle stock turnover rate (%) (2020-2035)	7	7	7	7	10	5	7	10	5	National Energy Board [24]; Author's judgement

3.2 Supply-side model

The vehicle supply model is designed to be a representation of the Canadian auto industry at the aggregate level. While it would be interesting to simulate and observe the behaviour of a heterogenous set of automakers (in future applications of this model), the present study is more concerned with the overall industry-wide impacts of policies (not impacts to specific automakers).

The objective for the aggregate automaker is to maximize the net present value of profits over the planning horizon, which we can set as any number of years within the modeling time horizon (in this case, from 2020 to 2035). In AUM, in a given year, the automaker looks forward with their planning horizon (currently the full time horizon to 2035), and makes several decisions relating to all drivetrain technologies, namely:

    i.   R&D investment,[35] which includes any investment costs (including capital and labour): that can contribute to lower ZEV costs nationally over time, in addition to the global exogenous decline in battery and other component costs;

    ii.   the number of ZEV models available for sale;

    iii.   charger deployment, where the automaker endogenously partly contribute to the exogenous increase in charging infrastructure; and

    iv.   the price of all vehicles sold, where the automaker adjusts relative prices of vehicles (e.g. by subsidizing ZEVs and adding a premium to conventional vehicles) while trying to maximize profits subject to policy.

The automaker seeks to maximize profits over the planning horizon T for all technologies 1 to K, specified as:

$$Profits = \sum_{t=1}^{T} \frac{1}{(1+i)^t} \sum_{k=1}^{K} [Q_{tk}(P_{tk}, n_{ctk}, CA_{ctk}).P_{tk} - C_{Ptk} - C_{Rtk} - C_{Itk}] \quad (4)$$

Where $Q_{tk}(P_{tk}, n_{ctk}, CA_{ctk})$ is the quantity of each vehicle type k produced in t^{th} time period and quantity is a function of price P_{tk}, and number of models n_{ctk} of the vehicle type k. n_{ctk} is endogenously added by the Canadian automaker, in addition to the exogenous increase in the number of models globally. Similarly, CA_{ctk} is the Canadian automaker's endogenous contribution to charging access (in percentage), in addition to the exogenous increase in charging access. The discount rate is 8%, which reflects the opportunity cost of capital for private firms.[37] The automaker thus adjusts P_{tk}, n_{ctk}, CA_{ctk} and C_{Itk} in equation (4) to maximize profits. The quantity of vehicles of each type produced is assumed to equal the quantity demanded in the consumer choice model. The inclusion of model variety feedback and endogenous charging deployment are additional novelties of AUM. The profit equation (4) also includes three cost terms ($C_{Ptk}, C_{Rtk}, C_{Itk}$), each of which is described briefly next.

First, C_{Ptk} is the total cost of production of a vehicle technology type k in time t given by the following equation. The quadratic cost curve equation indicates the effect of diseconomies of scale as follow:

$$C_{Ptk} = C_{0tk} * Q_{tk}(P_{tk}, n) + a * Q_{tk}(P_{tk}, n)^2 \quad (5)$$

Where C_{0tk} is the cost of production of a single vehicle of type k in time t, a is a scaling constant (Table 3) and $Q_{tk}(P_{tk}, n)$ represents the total quantity of vehicles of type k produced in time t.

Table 3: Exogenous parameters used in the automaker model

Parameters	Value	Source
Scaling parameter, a (equation 5) conventional vehicles (CVs)	0.01	Authors' judgement, based on model calibration to 2020 actual CV market share
Scaling parameter, a (equation 5) PEVs	0.02, decreasing linearly to 0.015 in 2030	Authors' judgement, based on model calibration to 2020 actual PEV market share;
Cumulative capacity (CC) CVs in 2020	25 million	Statistics Canada (2020)
Cumulative capacity (CC), PEVs in 2020	100,000	Statistics Canada (2020)
Knowledge Stock (KS), CVs in 2020	$500 billion	Authors' calculation; based on Barreto and Kypreos (2004)[35]
Knowledge Stock (KS), PEVs in 2020	$3 billion	Authors' calculation; based on Barreto and Kypreos (2004) [35]

The second cost term in equation (4), C_{Rtk}, indicates the total regulation costs related to policy. We endogenously model the ZEV standard and vehicle emissions standard as part of the profit function. The regulation cost associated with the ZEV standard is then modelled as $\rho_{ZEV} * (\emptyset_{ZEV} * Q_{Total} - Q_{ZEV})$, where ρ_{ZEV} is the penalty per ZEV credit below the stipulated quota, $\emptyset_{ZEV}$ is the minimum ZEV credits required by the quota (e.g. 4%), Q_{Total} is the total number of vehicles sold by the automaker, and Q_{ZEV} is the total number of zero-emission vehicles sold by the automaker. For vehicle emission standards, similarly, the regulation cost is $\rho_{FE} * Q_k * (Z_{FE} - Z_k)$, where ρ_{FE} is the penalty, Q_k is the number of vehicles of drivetrain technology k that are sold, Z_{FE} is the fuel economy limit, and Z_k is the fuel economy of vehicle k. The total regulation cost is given by:

$$C_{Rtk} = \rho_{ZEV} * (\emptyset_{ZEV} * Q_{Total} - Q_{ZEV}) + \rho_{FE} * Q_k * (Z_{FE} - Z_k) \quad (6)$$

The third cost component in equation (4) above, C_{Itk} represents the Canadian automakers' R&D investment. We assume that the cost of production (C_{0tk} in equation 5 above) of vehicles produced in Canada can be in part influenced by the investment in research, C_{Itk} made by automakers nationally over time (apart from the exogenous decline in vehicle costs due to global efforts), as follows:

$$C_{0tk} = \{\gamma_k * C_{0t-1,k} * [CC_{t-1k}^{-LBD} + KS_{t-1,k}^{-LBS}]\} \quad (7)$$

The cost of production for each drivetrain technology, C_{0tk} has two separate components affecting the evolution of costs over time. First, capital costs can decline as a result of production

occurring elsewhere in the world, where γ_k represents the annual rate of exogenous (global) decline in the cost of production. Therefore, a vehicle's costs can still decline over time despite little to no production or investment occurring in Canada. Second, production costs decline endogenously as a result of an increase in the cumulative production and research investment in that technology in Canada. The cost of production of each drivetrain technology C_{0tk} in time t is affected (endogenously) by the cost of production in the previous year $C_{0t-1,k}$, cumulative capacity CC_{t-1k} (total number of vehicles of technology k produced up to time t-1 in Canada) as well as knowledge stock $KS_{t-1,k}$ (synonymous with cumulative R&D investment in Canada) achieved up to period t-1.

Thus, while on the one hand, investing in research increases automaker's costs in the present, on the other hand, such investment potentially reduces future production costs. When optimizing over the planning horizon, the automaker can trade-off between increased research costs in the present versus benefits from lower costs of production at a later date. The initial capital costs, initial knowledge stock, initial cumulative capacity, learning by doing (LBD), and learning by searching (LBS) values are exogenously specified in the model (Table 3).

3.3 Calculating GHG emissions

We follow several additional steps to calculate total light-duty vehicle GHG emissions. We calculate the total stock of vehicles, the usage of those vehicle and then finally assign GHG values to those vehicles.

First, the total stock (S_{tk}) of vehicles of each technology type k surviving from year t to year $t+1$ is given by:

$$\sum_{k=1}^{N} S_{t+1,k} = \sum_{k=1}^{N} S_{t,k} (1-d_{t,k}) + \sum_{k=1}^{N} Q_{t,k} \tag{8}$$

where $d_{t,k}$ = stock turnover rate in time t for technology k; Q_{tk} is the quantity of new vehicles of technology k at time t.

Second, vehicle use (or travel demand) depends upon fuel costs. An increase in fuel costs (e.g. due to a tax) can decrease travel demand, while a reduction in fuel costs (e.g. due to fuel economy improvement) can increase travel demand. We use elasticity (e) to represent how consumers adjust vehicle usage rates as a result of changes to the cost of driving. The elasticity of travel demand is depicted in Table 2. The vehicle use under policy (V_p) is a function of the projected travel demand in the reference no policy case (V_0), the elasticity parameter (e), and the changes to the fuel cost in the policy scenario relative to the reference case, given by:

$$V_p = V_0 \left(\frac{fuel\ cost_P}{fuel\ cost_0} \right)^e \tag{9}$$

where $fuel\ cost_P$ is the fuel cost under policy, while $fuel\ cost_0$ is the fuel cost in the reference no policy case. The reference case vehicle use (V_0) in Canada is assumed to be 16,000 km a year, based on data from Statistics Canada.

Once the vehicle stock and vehicle use values are known, the total GHG emissions can be obtained by multiplying the product of vehicle stock and vehicle use values with the energy consumption per vehicle and fuel carbon intensity. The vehicle energy intensity for each drivetrain is set exogenously for each drivetrain based on data from the U.S. EIA (2020) and the National Energy Board (2019) – as shown in Table 4.[24,25] For PHEVs, we assume that consumers use electricity to run the PHEVs 70% of the time and use gasoline for the remaining 30%, which translates to a 70% "utility factor". Plotz et al.[38] calculate this utility factor from real world driving data across several countries, and find that utility factors vary with the electric range, and across countries (e.g, for a 100-kilometer electric range PHEV, utility was about 70% in Canada and Norway, but only 40% in China and Netherlands). To account for uncertainty in our sensitivity analysis, we assume the utility factor is 50% in the pessimistic case, and 90% in the optimistic case – however, in each scenario, the split is exogenous and does not respond to changes in fuel or electricity prices.

Table 4 Vehicle energy intensity and fuel carbon intensity (Canadian) assumptions			
	2020	**2035**	**Source**
Vehicle energy intensity			
Conventional (L/100 km)	7.55	5.73	National Energy Board (2019), EIA (2020)
PHEV (L/100 km: 30% Gasoline)	2.2	1.63	National Energy Board (2019); EIA (2020)
PHEV (kWh/100 km: 70% electric)	0.13	0.10	National Energy Board (2019); EIA (2020)
BEV-320 (kWh/100 km)	0.19	0.16	National Energy Board (2019)
Carbon intensity (gCO_2/MJ)			
Gasoline (with Clean Fuel Standard)	88.1	76	Government of Canada (2021)
Electricity	19.5	14	National Energy Board (2019); GHGenius

Table 4 also summarizes our exogenous assumptions about the WTW carbon intensity of each fuel, which include the GHGs emitted in the process of producing a fuel and transporting it to the point at which it enters a vehicle for consumption in Canada, based on GHGenius (version 5.05b) model and other literature cited above (National Energy Board, 2019; EIA, 2020). Carbon intensity decreases over time under the effect of the Clean Fuel Standard. For electricity, it is assumed that the contribution of low-carbon, renewable sources in electricity production will increase in the future in Canada, stimulated by national policies to replace coal and natural gas fired power plants in the electricity sector.[24]

3.4 Uncertainty analysis

We follow multiple steps to explore and depict uncertainty in results, namely we: (i) identify key parameters (listed below) causing the most uncertainty in model outputs; and (ii) depict some results as uncertainty bands with pessimistic and optimistic value assumptions of the input

parameters determining the boundaries of these uncertainty bands. We test the effect of pessimistic and optimistic estimates drawn from literature (optimistic/pessimistic values are listed in Tables 2 and 3).

The key parameters affecting model results are:

1. **Battery pack costs**: As seen by car manufacturers (including markups from battery manufacturers), costs are $230/kWh in 2020, and $180/kWh in both 2022 and 2023.[29,30] The higher 2022 and 2023 prices reflect the current supply chain issues being observed for advanced automotive batteries. Industry reports suggest that this is a temporary issue and may be resolved by 2023, so our assumptions resume the long-term trajectory of battery price decline in 2024 – with a two-year delay from previous estimates. That is, instead of battery prices reaching $50/kWh in 2030 (as assumed in our most recent report using AUM),[39] we now assume the benchmark is reached 2 years later in 2032. For the uncertainty analysis, we assume values of 40 CDN$/kWh (optimistic) and $100/kWh (pessimistic) in 2035, [29] similar to Lutsey et al.[28]

2. **Price elasticity** of demand: determining how vehicle ownership is affected in response to vehicle prices, assume values of -0.3 (optimistic) and -1 (pessimistic), corresponding to the low and high values suggested in literature.[31,32]

3. **Discount rate**: It is used by the automaker assumes values of 8% (optimistic) and 15% (pessimistic), corresponding to the low and high values suggested in Jagannathan et al. (2016).[36]

4. **Fuel prices** (gasoline price, exclusive of carbon price) are taken to be $0.83 per litre in 2020, $1.78/L in 2022, and $1.60/L in 2023. For 2035 we include a range of prices from $0.65 to $1.70. [24-27,40]

5. The **Consumer preferences** parameter, representing the endogenous change of ASC over time, varies across consumer segments (Table 1). As an example, the consumer preference for BEVs among the "Resistors" consumer segment is -$40,000 in 2020, and assume a base value of -$13,000, with -$20,000 as pessimistic and $0 as optimistic values in 2035.

6. The exogenous global increase in **model variety** for PEVs is assumed to grow from 10% (relative to model availability for conventional vehicles) in 2020, to assume values of 60% (pessimistic) and 100% (optimistic) in 2035.

7. The **Recharging access** parameter indicates the locational availability of public charging infrastructure, relative to existing gasoline infrastructure: it is 10% in 2020. The 2030 values are 70% in the median scenario, 50% in the pessimistic scenario, and 90% in the optimistic scenario. Values in 2035 range from 60% (pessimistic) to 100% (median and optimistic).

8. The **Domestic Rate of learning** parameter, which in AUM determines the rate at which technology improves in Canada, partly (in addition to global efforts) affecting how quickly domestic vehicle manufacturing costs drop over time, in response to increased domestic production (learning by doing) or domestic investment in R&D (learning by searching) (see equation 8 for reference). Since part of the decline in vehicle costs is assumed to be exogenous (due to global factors), this rate of learning can be understood to be the domestic learning rate. The Rate of Learning parameter assumes values of 6%

(pessimistic) and 10% (optimistic), +/-25% relative to the median value of 8%.[34] These values are constant from 2020 to 2035.

9. The **stock turnover rate** indicates the exogenous rate at which existing vehicles are assumed to retire annually. We assume it varies between 5% (pessimistic) and 10% (optimistic) between 2020 and 2035.

10. **Vehicle-kilometres travelled (VKT) elasticity of demand** determines how vehicle travel is affected in response to fuel costs: it assumes values of -0.15 (optimistic) and -0.25 (pessimistic) between 2020 and 2035.

11. **Carbon intensity of gasoline (in gCO$_2$e/MJ),** assumes values of 76 gCO2e/MJ (optimistic) and 82 gCO$_2$e/MJ (pessimistic)

4. Policy scenarios

Our analysis includes a total of six policy scenarios.

First is **a baseline scenario**, which only uses current policies. Although individual provinces are not currently represented in AUM, we will account for some provincial-based policies (British Columbia [BC] and Quebec ZEV standard). Specifically:

- Carbon tax: $50 in 2022, increasing by $15 annually until it reaches $170 in 2030, where is stays until 2035.
- Clean Fuel Standard (CFS): reflecting the announced CFS policy from early July 2022, where the carbon intensity of liquid fuels will be reduced by 3.5 gCO$_2$e/MJ in 2023, with increasing reductions reaching 14 gCO$_2$e/MJ by 2030 (i.e. Gasoline pool carbon intensity = 93.9 gCO$_2$e/MJ in 2021 and 2022; 91.5 in 2023; 81.0 gCO$_2$e/MJ in 2030).[8] We also account for the BC low-carbon fuel standard, which is more stringent than the CFS by 2030 (76 gCO$_2$e/MJ). Including that, the total Canada-wide requirement would be 80.5 gCO$_2$e/MJ).
- ZEV standard: we translate provincial ZEV standards to national equivalent (update to 100% for 2035 in BC and Quebec). This is equivalent to 21% national ZEV standard in 2030 and a 36% national ZEV standard in 2035.
- Purchase incentives: we include national and provincial ZEV purchase incentives in terms of estimated amount and duration (and total population weighted average for Canada), as shown in Tables 5a and 5b.
- Charging deployment: we assume that 70% of drivers have access to charging by 2030, though uncertainty analysis considers ranges from 50% to 90%. Values in 2035 range from 60% (pessimistic) to 100% (median and optimistic).

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8 See parameters in Table 1 of https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/clean-fuel/regulations/CFR_CG_II_Unofficial_Version_2022-06.pdf

- Vehicle emissions standard (VES): following recent "Biden-era" standards, the schedule is as follows (where the 2026 values are held constant until the end of the modeling period, 2035):[9]
    2020: 140 gCO$_2$e/km
    2021: 134 gCO$_2$e/km
    2022: 132 gCO$_2$e/km
    2023: 119 gCO$_2$e/km
    2024: 113 gCO$_2$e/km
    2025: 107 gCO$_2$e/km
    2026-2035: 102 gCO$_2$e/km (starting in this year, 'effective' fuel economy held constant for non-ZEVs)

Second is a **"Stringent ZEV standard":** to this baseline, we add a ZEV standard in 2023 as follows:
- Annual compliance to sales targets outlined by the national government: 20% by 2026, 60% by 2030 and 100% LDV ZEV sales by 2035.
- Penalty for non-compliance: $20,000 per credit
- ZEV credit system:
    o BEVs sale: 1 credit (any range)
    o PHEV: 0.5 credit
        ▪ Max 10% PHEV credits allowed from 2023-2029
        ▪ No credits for PHEVs allowed from 2030-2035
    o Automakers can bank credits for up to 3 years

Next are three durations of a **"Subsidy-based strategy":** where the national iZEV purchase incentives are tripled, up to $15,000 for BEVs, as well as PHEVs with range greater than 50 km.
- Short-term: 2023-2026 (which can be called "Phase out at price parity" scenario)
- Medium-term: 2023-2030
- Longer-term: 2023-2035

Finally, we include one scenario that combines the stringent ZEV standard with the "longer-term" subsidy-based strategy above.

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[9] We acknowledge the complexity of potential interactions between a VES and ZEV standards. In this report, we are modeling the VES as separate from ZEV sales – that is, additional ZEV sales are not allowed to earn credit in the VES. The VES requirements are applied to the remaining non-ZEV portion of vehicles sold.

Table 5a: Assumed baseline BEV purchase subsidies (weight by vehicle sales per region)

Jurisdiction	2020	2021	2022	2023	2024	2025	2026	2027-35	Sources:
Canada	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000	0	https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles/incentives-purchasing-zero-emission-vehicles
BC	$3,000	$3,000	$3,000	$3,000	$3,000			0	https://goelectricbc.gov.bc.ca/
QC	$7,000	$7,000	$7,000	$7,000	$7,000	$7,000	$7,000	0	https://vehiculeselectriques.gouv.qc.ca/rabais/ve-neuf/programme-rabais-vehicule-neuf.asp
Nova Scotia	$3,000	$3,000	$3,000	$3,000				0	https://evassist.ca/rebates/
New Brunswick			$5,000	$5,000				0	https://www.nbpower.com/en/products-services/electric-vehicles/plug-in-nb/electric-vehicle-rebates/
PEI	$3,750	$3,750	$5,000	$5000				0	https://www.princeedwardisland.ca/en/information/environment-energy-and-climate-action/electric-vehicle-incentive
NFL	$2,500	$2,500	$2,500	2,500				0	https://nlhydro.com/electric-vehicles/ev-rebate/
Yukon	$4,000	$4,000	$5,000	$5,000				0	https://yukon.ca/en/driving-and-transportation/apply-rebate-new-zero-emission-vehicle
Weighted total	$7195	$7195	$7255	$7255	$7118	$6695	$6695		

Table 5b: Assumed baseline PHEV purchase subsidies (weight by vehicle sales per region)[10]

Jurisdiction										
Canada	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000		0	https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles/incentives-purchasing-zero-emission-vehicles
BC	$3,000	$3,000	$3,000	$3,000	$3,000				0	https://goelectricbc.gov.bc.ca/
QC	$5,000	$5,000	$2.5-5k	$2.5-5k	$2.5-5k	$2.5-5k	$2.5-5k		0	Note: $2,500 for <15,00 Wh, otherwise $5,000 https://vehiculeselectriques.gouv.qc.ca/rabais/ve-neuf/programme-rabais-vehicule-neuf.asp
Nova Scotia	$3,000	$3,000	$3,000	$3,000					0	https://evassist.ca/rebates/
New Brunswick			$5,000	$5,000					0	https://www.nbpower.com/en/products-services/electric-vehicles/plug-in-nb/electric-vehicle-rebates/
PEI	$3,750	$3,750	$2,500	$2,500					0	https://www.princeedwardisland.ca/en/information/environment-energy-and-climate-action/electric-vehicle-incentive
NFL	$2,500	$2,500	$1,500	$1,500					0	https://nlhydro.com/electric-vehicles/ev-rebate/
Yukon	$4,000	$4,000	$5,000	$5,000					0	https://yukon.ca/en/driving-and-transportation/apply-rebate-new-zero-emission-vehicle
Weighted total (<15,000 WH)	$6,711	$6,711	$6,104	$6,104	$5,951	$5,606	$5,606			
Weighted total (>15,000 WH)	$6,711	$6,711	$6,712	$6,712	$6,556	$6,211	$6,211			

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[10] PHEVs modeled by AUM are all "longer range" in the federal definition (60 to 120 km).

5. Results and discussion

Tables 6 and 7 are summary tables of several key outputs for each policy scenario. Both tables have only median outputs, which don't account for the uncertainty ranges described in Section 3.5. These tables provide an overall summary of the impacts of each policy scenario, and the trade-offs involved in selecting one over another. The following sections go into more detail of results for ZEV sales, GHG emissions, automaker impacts (profits, markups, sale prices and R&D investment), and subsidy expenditure.

5.1 ZEV Sales

Figure 2a portrays results for ZEV new market share in the baseline, ZEV standard, and three subsidy-based scenarios. Figure 2b separately depicts the combined ZEV standard and longer-term subsidy scenario. Each shaded area incorporates the uncertainty analysis described in Section 3.5, where the upper ZEV sales boundary utilizes the "optimistic" parameter assumptions, and the lower boundary utilizes the "pessimistic" assumptions. Table 6 summarizes the median ZEV new market share numbers for each scenario relative to ZEV target years (2026, 2030, and 2035)

Clearly, the current "baseline" policy scenario is not nearly strong enough to meet ZEV sales goals in 2026, 2030 or 2035. These policies lead to only 15-17% ZEV new market share in 2026 (16% median), 23-27% new market share in 2030 (25% median), and 35-43% new market share in 2035 (39% median).

Table 6: ZEV new market share in each policy scenario (median scenario)

|	2026	2030	2035
Emission Reduction Plan Sales Target	20%	60%	100%
Baseline	16%	25%	39%
ZEV Standard	25%	59%	98%
Subsidy (short)	20%	29%	47%
Subsidy (med.)	20%	34%	54%
Subsidy (long)	20%	36%	65%
+ ZEV standard + subsidy (long)	25%	59%	98%

Relative to this baseline, all three subsidy-based scenarios lead to increased ZEV sales in each year following the initial tripling of national subsidies in 2023. However, the 2030 and 2035 ZEV sales goals are still not met by any subsidy version, even under optimistic assumptions. The shorter-term subsidy (in place until 2026) reaches 27-30% sales by 2030, and 44-49% by 2035. Continuing the subsidies until 2030 increases 2030 ZEV sales to 32-36%, and 2035 sales to 51-57%. An extension of the subsidies to 2035 further increases ZEV sales to 34-38% in 2030, and 62-69% in 2035

In contrast, the ZEV standard scenario exceeds the 2026 ZEV sales target, and achieves or comes very close to achieving 2030 and 2035 sales goals. Sales are increased to 56-62% in 2030, and 96-100% in 2035. The combination of a ZEV standard and longer-term subsidy leads to a similar outcome (Figure 2b), with 56-61% ZEV sales in 2030, and 95-100% sales in 2035.

Table 7: Policy scenario summary (median scenario, all prices in Canadian dollars)

		Baseline	+ ZEV standard	+ Subsidy (short)	+ Subsidy (med)	+ Subsidy (long)	+ ZEV standard + Subsidy (long)
Effectiveness:							
ZEV sales	**2035 % of new sales**	38%	97%	47%	54%	65%	98%
GHG emissions	**2035 Mt**	47.3	28.4	46.3	43.5	41.7	28.9
	2022-35 Mt	771	636	756	733	732	643
Automaker impacts:							
Profits	**2035 $ billion,**	24.0	19.4	24.5	24.9	25.5	21.0
	2023-35 $ billion	268	248	270	274	279	257
Vehicle markups	**(%, 2035) ZEV**	34%	22%	35%	37%	39%	29%
	(%, 2035) ICE	41%	44%	40%	39%	39%	42%
ZEV prices	**Avg. % change from base**		-22%	-10%	-20%	-31%	-28%
	Avg. $ change from base		-$7,241	-$3,673	-$6,742	-$9,942	-$8,942
ICE prices	**% change from base**		+6.1%	-0.7%	-3.4%	-7.8%	+2.5%
	Avg. $ change from base		+$1,876	-$222	-$1,032	-$2,347	+$702
R&D Investment	**2023-35 $ billion**	3.3	6.9	3.3	3.4	3.5	5.8
Subsidy details:							
Gov't expenditure	**2023-35 $ billion**	2.5	2.5	8.1	24.1	54.1	82.3
Capture by automakers	**2023-35 (%)**	10%	10%	13%	14%	18%	14%

Figure 2a: ZEV market share in new vehicle sales (individual policies, uncertainty range)
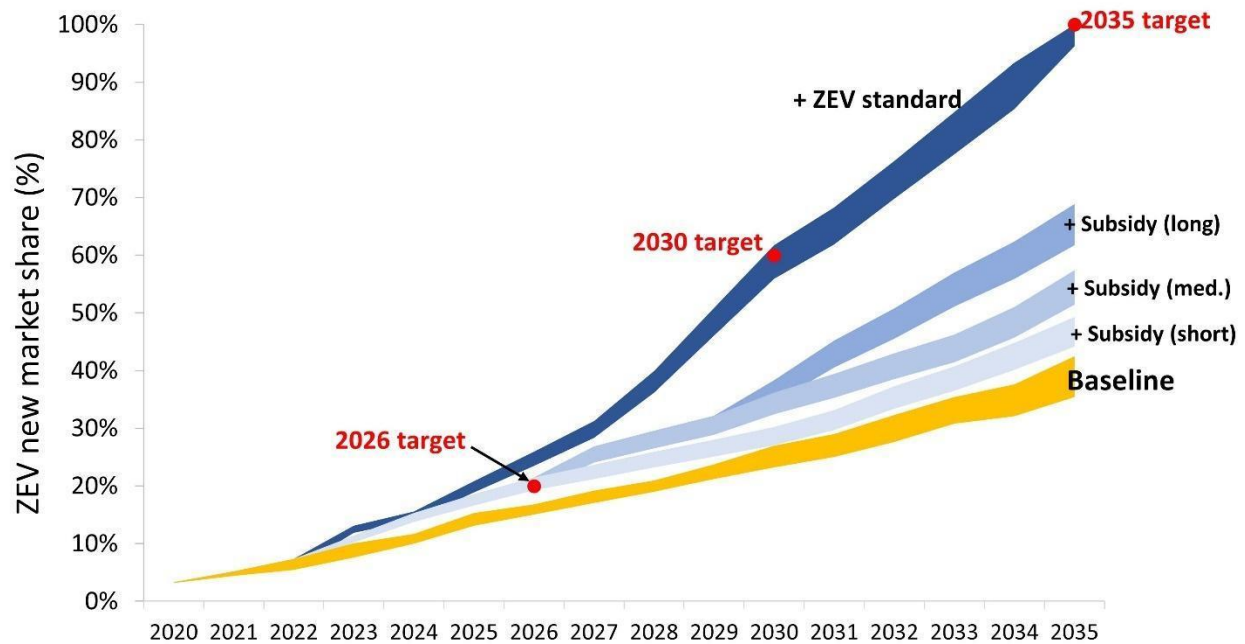
Figure 2b: ZEV market share in new vehicle sales (combined policy, uncertainty range)
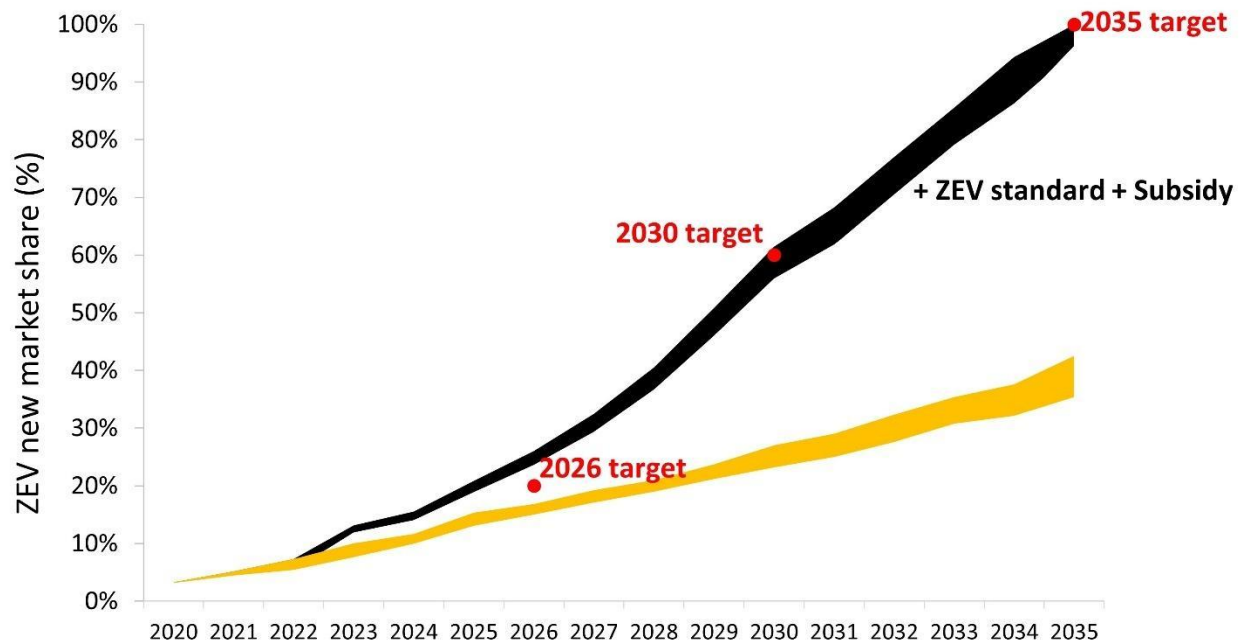

Note that the ZEV scenarios can fall short of the sales goals in 2030 or 2035 by several percentage points for two possible reasons: i) automakers are banking credits from over-compliance in earlier years to comply with later requirements (applies to 2030 only), and/or ii) automakers choose to pay the penalty of $20,000/credit for non-compliance, as this is cheaper than further subsidizing their ZEVs (or following other compliance pathways) to the amount

needed to sell ZEVs this last few percent of consumers. Due to the heterogeneity among consumer preferences, it is difficult to sell ZEVs to a small section of the "resistors" (See Section 3.1). Although automakers can increase the price of conventional vehicles, increasing price too much will reduce overall vehicle sales and profits. Automakers consider the trade-off between foregoing profits due to lost sales and paying fines, choosing to pay fines for a small portion of non-complying sales relative to the requirement.

5.2 GHG emissions

Figures 3a and 3b depict the GHG emissions from Canada's light-duty vehicles in all policy scenarios. These emissions include the total stock of light-duty cars and trucks, not just the new vehicles sold in each year. If strong climate policies are kept in place, annual light-duty vehicle GHG emissions would continue to decline past 2035 (not modeled or depicted), as the full stock of vehicles transitions to ZEVs. This analysis also includes the potential for policies to increase overall vehicle sales if the average price of vehicles is lowered (e.g., in a subsidy scenario), as well as decrease overall vehicle sales if vehicle prices on average are increased (e.g., under a standard or tax scenario).

Figure 3a: Light-duty vehicle GHG emissions (individual policies, uncertainty range)
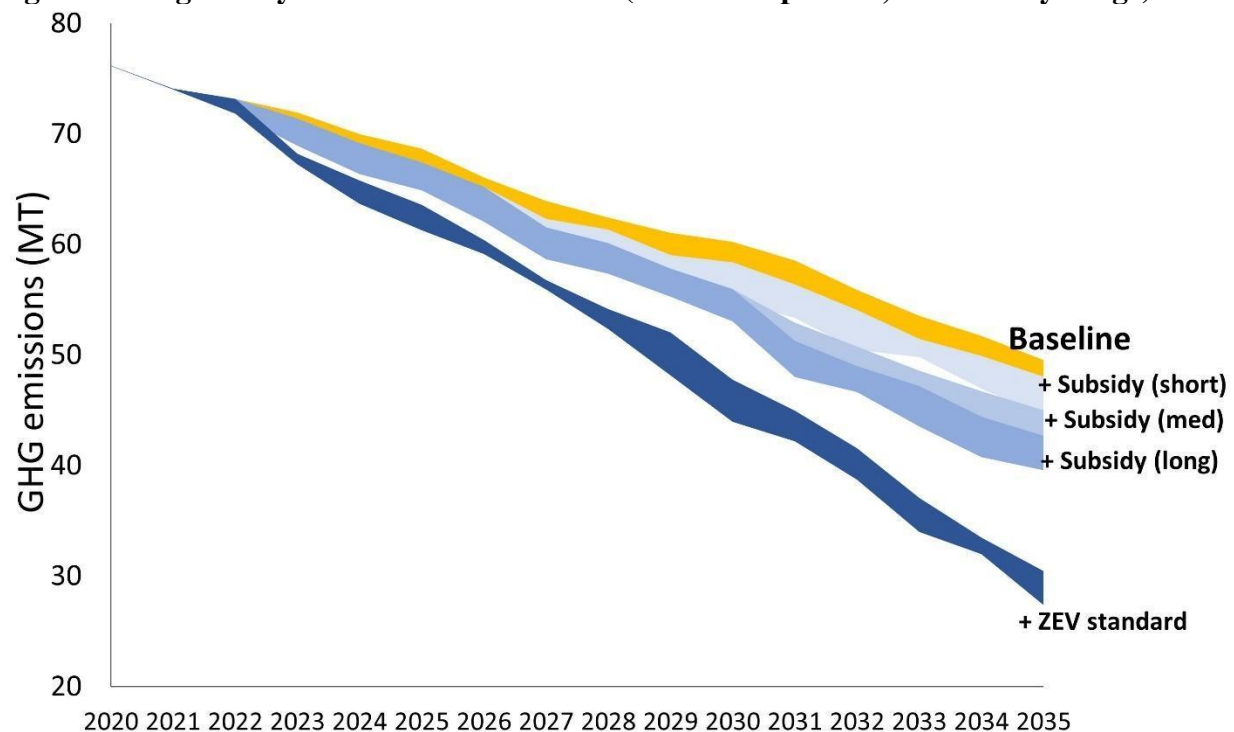

Under the baseline, existing policies are found to reduce emissions by 32-37% in 2035 relative to 2022 levels. The subsidy-based scenarios reduce 2035 light-duty GHG emissions by 34-38% in the short-term subsidy scenario, 39-42% in the medium-term scenario, and 42-45% in the longer-term scenario. The modeled ZEV standard results in a 58-62% decline in annual light-duty

transportation GHG emissions from 2022 levels by 2035. The combined standard and subsidy scenario is very similar (Fig 3b), reducing 2035 emissions by 59-62%.

In terms of cumulative emissions compared to the baseline (2023-2035), the subsidy scenarios induce GHG reductions of 11-19 Mt in the short-term subsidy, 35-41 Mt in the medium-term subsidy, and 39-50 Mt in the longer-term subsidy. The ZEV standard induces GHG reductions that are three to ten times greater, at 123-137 Mt.

Figure 3b: GHG emissions in new vehicle sales (combined policy, uncertainty range)
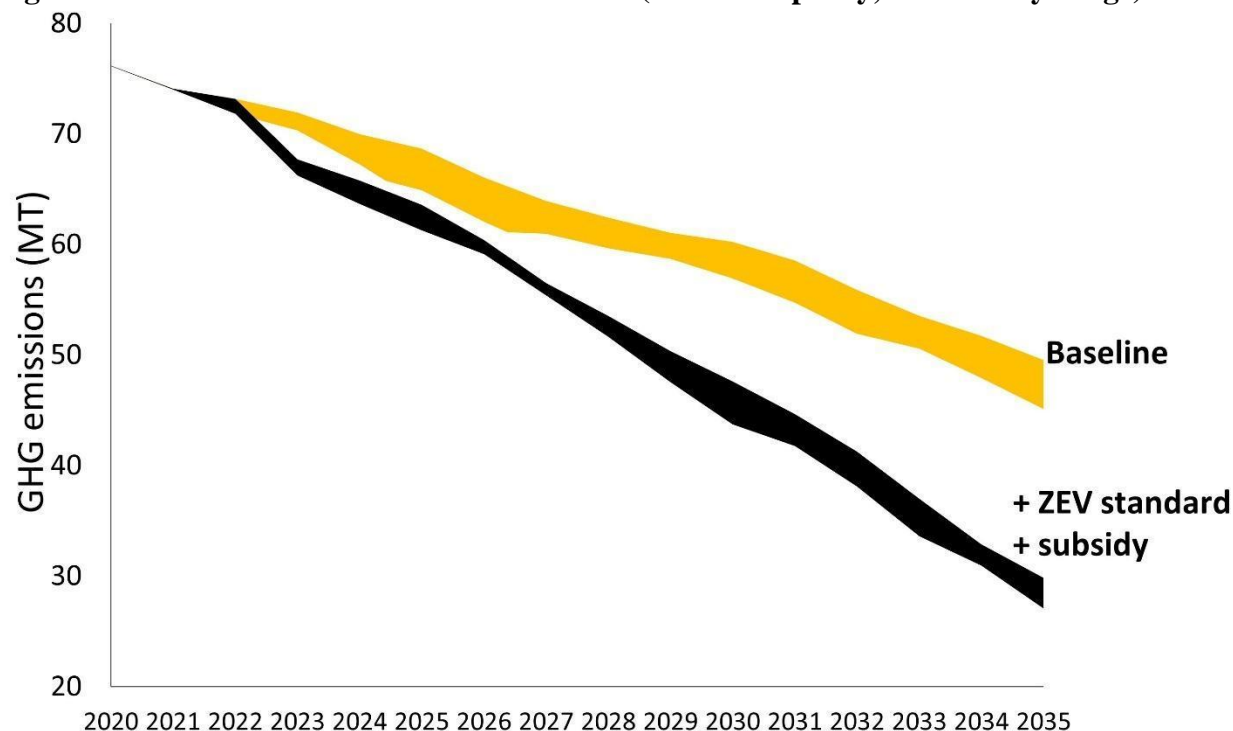

5.3 Automaker impacts: Profits, markups, vehicle prices, and R&D investment

In all scenarios, median automaker profits are higher in 2035 compared 2022 (Fig. 4). Compared the baseline, cumulative profits (2023-2035) are increased in the subsidy scenarios by 1-4%. Part of this profit increase is explained by automaker capture (or "incidence") of the subsidies, noted in Section 5.4. Further, making vehicles (ZEV and ICE vehicles) cheaper on average can increase total light-duty vehicle sales.

In contrast, the ZEV standard decreases cumulative profits by 7.5%. Profits losses result from the automaker changing their practices (pricing, R&D investment, and other strategies) relative to the baseline, as well as due to fewer vehicles sales and lower ZEV profit margins for the initial years and additional R&D costs in the initial years. Though, in the ZEV standard, annual automaker profits still increase by 15% from 2022 to 2035—due to the assumption of continued growth in vehicle sales in the long-term.

The combined standard and subsidy scenario reduces cumulative profits by only 4.2%—effectively reducing the profit impact compared to the ZEV standard alone.

Figure 4: Automaker profits (median simulations).
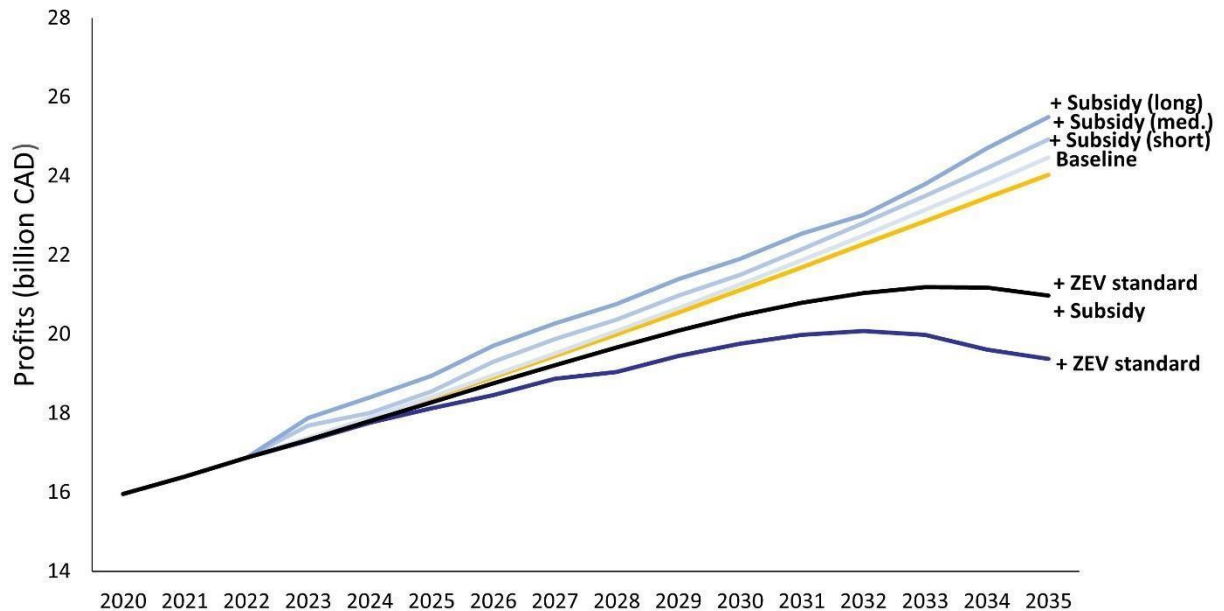
The vehicle "markup" is the percentage difference between the vehicle sales prices, and the manufacturing costs (Fig. 5). We do not distinguish between what portion of this is taken to automakers, dealerships, or other firms. Under all scenarios, ZEV markups are gradually increased from 2023 to 2035 as the technology becomes more mature. Compared to the average markup of 25% in the baseline from 2023-2035, the ZEV standard induces lower average ZEV markups of 18%, while increasing the average markup of ICE vehicles to 38%. This pattern indicates that automakers "cross-price" subsidize their vehicles in order comply with the ZEV standard—that is, they charge more for ICE vehicles so that they can lower the prices of ZEVs, thus shifting their sales shares towards ZEVs.

In contrast, the subsidy-based scenarios lead to an average increase of ZEV markups to 27% during that period (due to partial industry capture of the subsidy). At the same time, markups for ICE vehicles are marginally decreased. In effect, the subsidy-based scenarios have the opposite effect as the ZEV standard on vehicle markups.
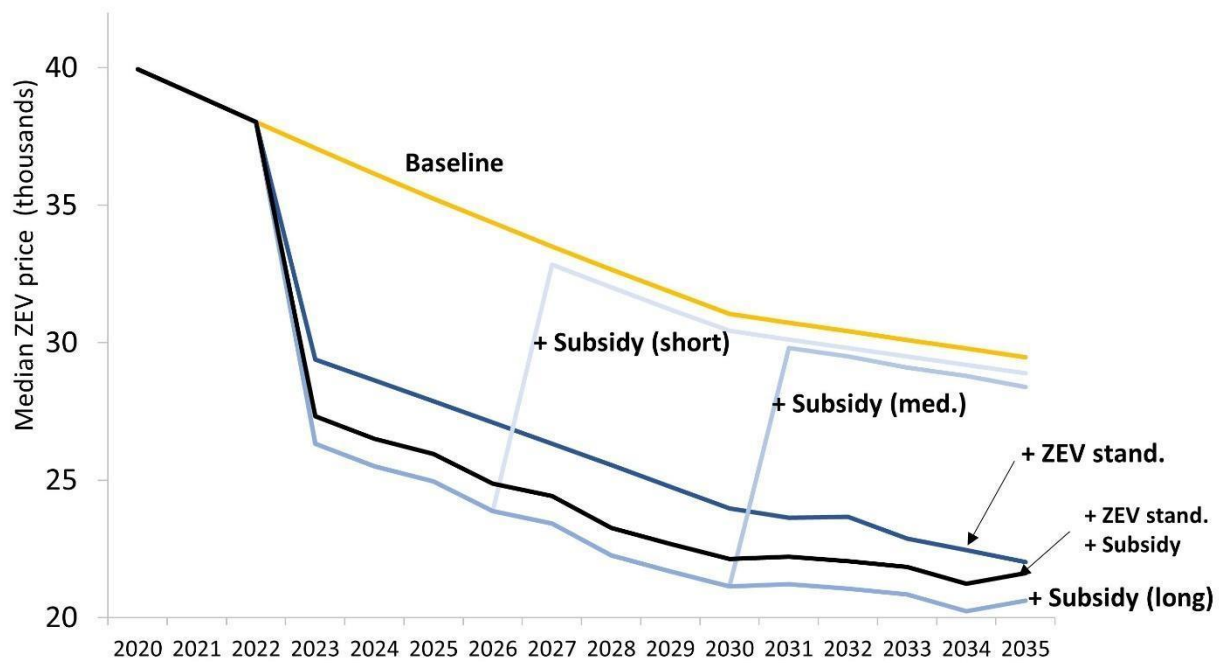
**Figure 5: Automaker markups (median simulations).**
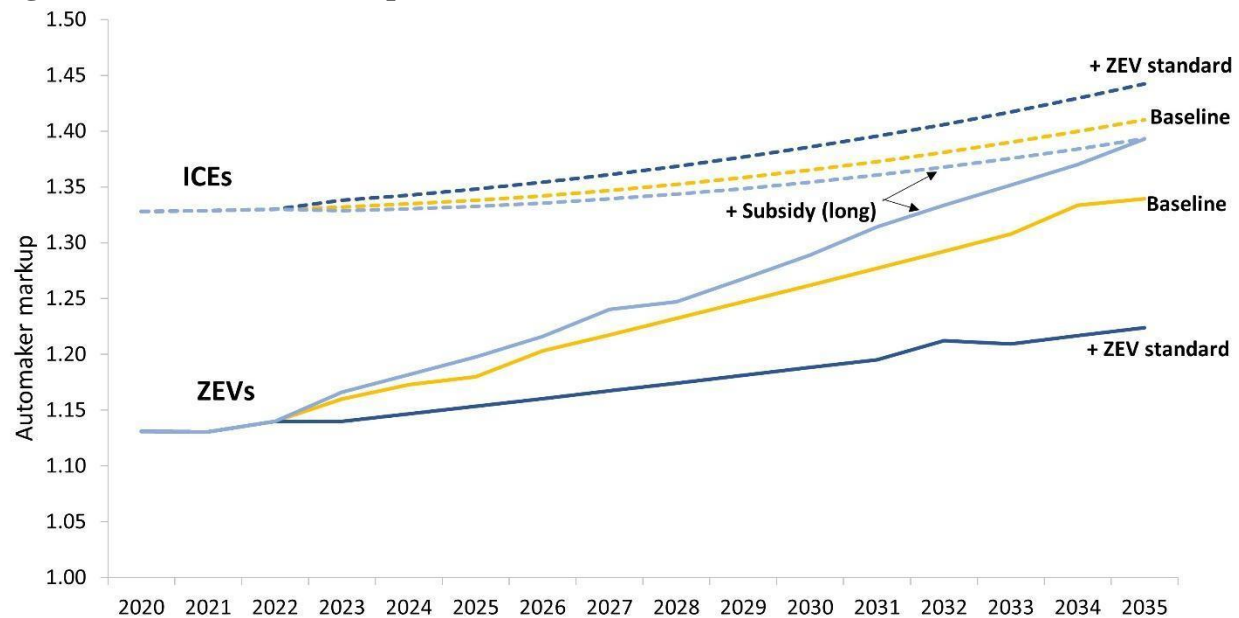
ZEV and ICE vehicle average sales prices follow a similar pattern as the markups (Figs 6 and 7). All policy scenarios induce a reduction in the sales price of ZEVs compared to the baseline. The ZEV standard leads to an average drop of about $7200 from 2023-2035 (a 22% reduction). At the same time, the ZEV standard induces automaker to increase the average price of ICE vehicles by 6% from the baseline scenario (from 2023-2035) to them to comply with the required sales targets.

In contrast, the subsidy scenarios induce an average ZEV price reduction of about 30% while the subsidy is in place, though ZEV sales prices return to similar levels as the baseline once the national subsidy is removed. The subsidy scenarios induce an average reduction of ICE prices of 1-8% (reductions of $200 to $2300 per vehicle on average), with the larger price reductions for the long-term subsidy.

**Figure 6: ZEV prices (median simulations)**

Figure 7: ICE prices (median simulations)
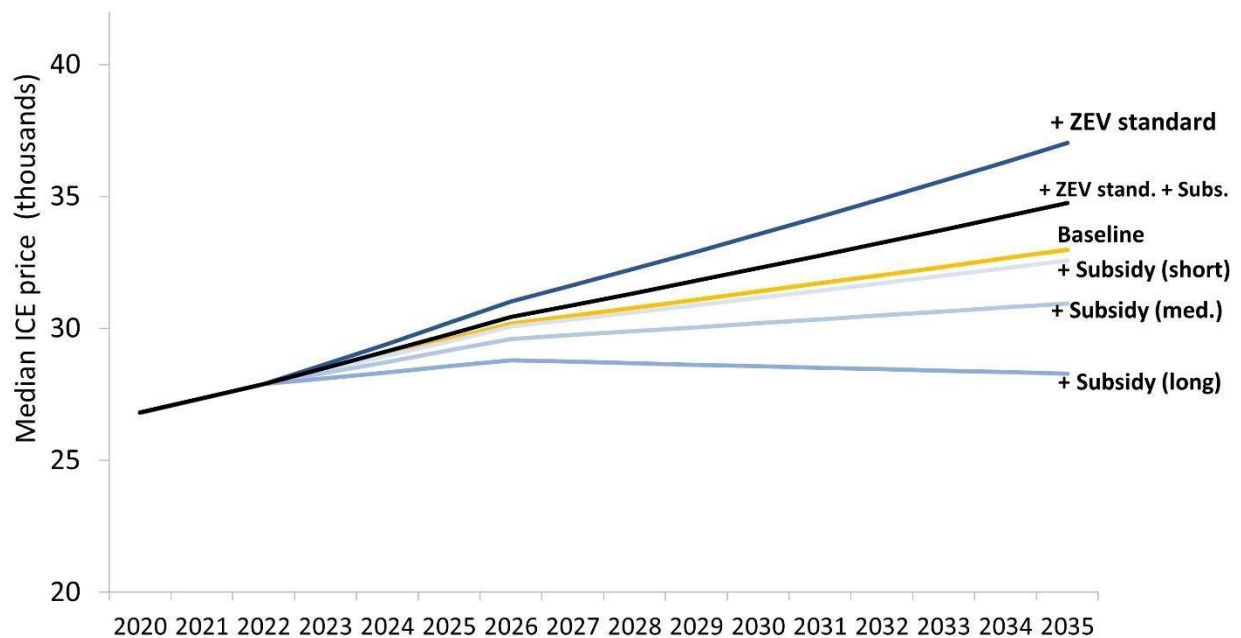
A final aspect of automaker profit that is considered here is investment in R&D related activities, which can include expenditures on both labour and capital in effort to reduce the costs of manufacturing ZEVs in Canada (Figure 8). Automaker investment in ZEV-related R&D is not

substantially impacted by any of the three subsidy-based scenarios. However, the ZEV standard induces an initial increase of R&D spending in 2023 by about 180%, and more than doubles the cumulative ZEV R&D spending from 2023-2035 compared to the baseline.

Figure 8: R&D Investment (median simulations)
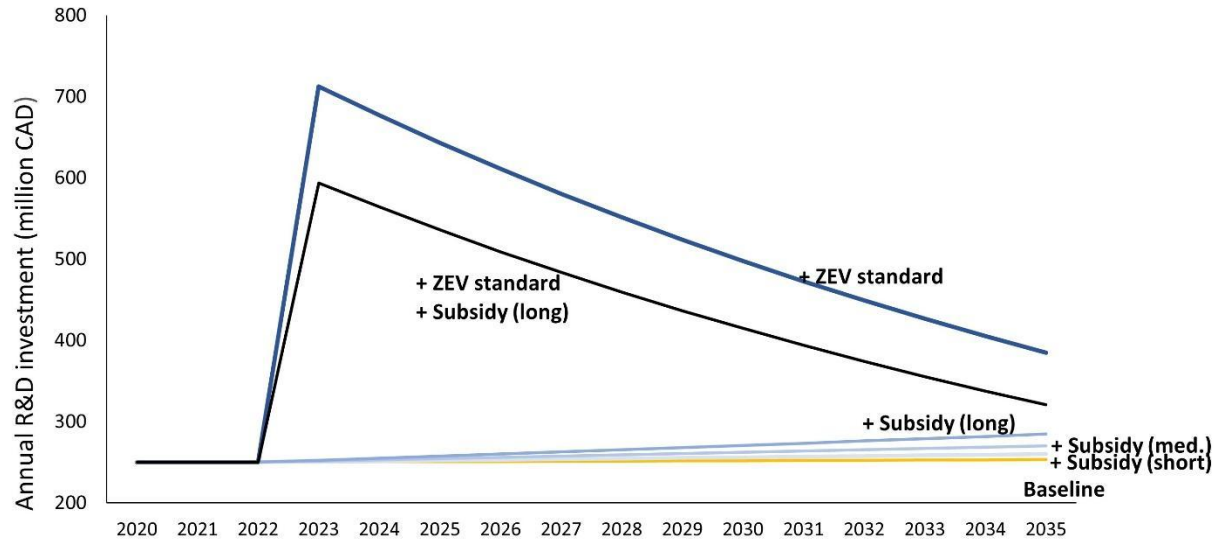
## 5.4 Subsidies: Government expenditure and automaker capture

In each scenario, the subsidy portion of each policy package requires billions of dollars in government expenditure in the modeled time horizon (summed from 2023 to 2035, undiscounted). The baseline and ZEV standard scenarios include current incentives, which are simulated to require about $2.5 billion in expenditure (Fig 9). When the national subsidy is tripled, government expenditure increases to $8 billion for the shorter-term subsidy, $24 billion for the medium-term subsidy, and $54 billion for the longer-term subsidy. Combining a ZEV standard and longer-term subsidy requires over $80 billion in government expenditure. This large cost results from the higher ZEV sales, multiplied by the subsidy provided for each ZEV sale.

Figure 9: Government expenditure (in billions of dollars, summed 2023-2035, undiscounted)
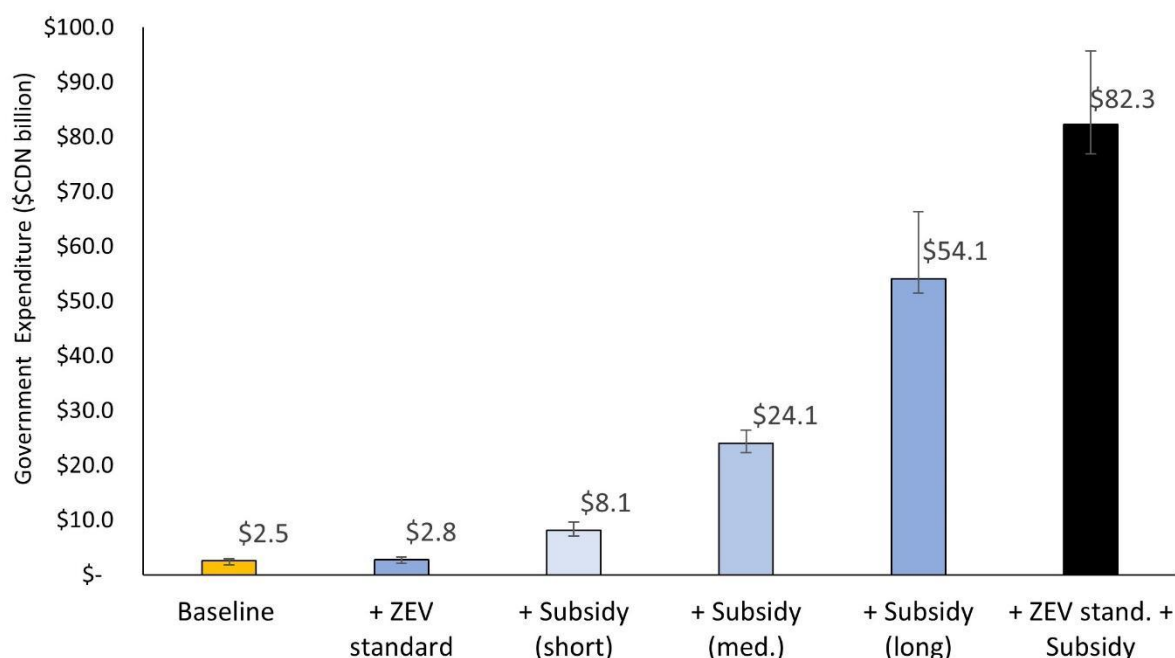
In the three subsidy-based scenarios, automakers (and potentially others in the auto industry) are found to capture 13-18% of the value of the purchase subsidies, with higher capture occurring for the longer-term subsidy (Figure 10). This range of values is similar to estimates and calculations found in published studies,[13] though is a bit higher than some other studies.[14,15]

Figure 10: Subsidy incidence, capture by automakers (in billions of dollars, summed 2023-2035, undiscounted)
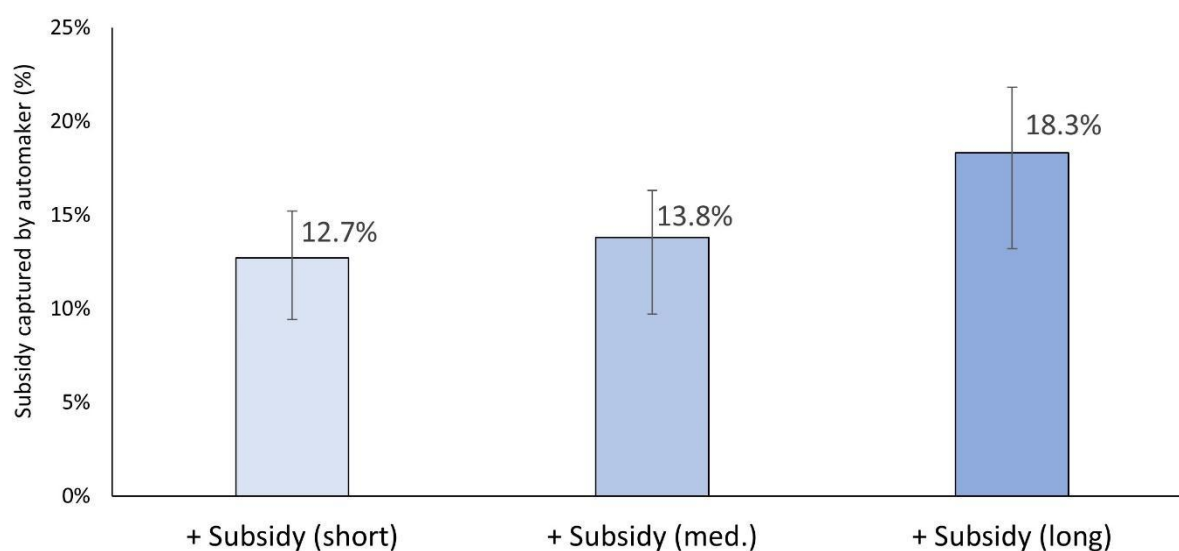
We also consider how the required government expenditure relates to the effectiveness of the subsidy scenarios in terms of inducing ZEV sales and GHG emissions reductions. This calculation is not a full economic "cost-effectiveness" analysis, but it provides a sense of some of

the trade-offs required for subsidy-based programs. First is government expenditure per additional ZEV sold, which amounts to over $32,000 per vehicle for all three subsidy-based scenarios (Fig 11). Other studies have found similarly high expenditure number, mainly due to free-ridership patterns where consumers that would have purchased the ZEV anyway are still entitled to the subsidy.[10,12]

Figure 11: Subsidy expenditure per additional BEV sale (thousands of dollars)
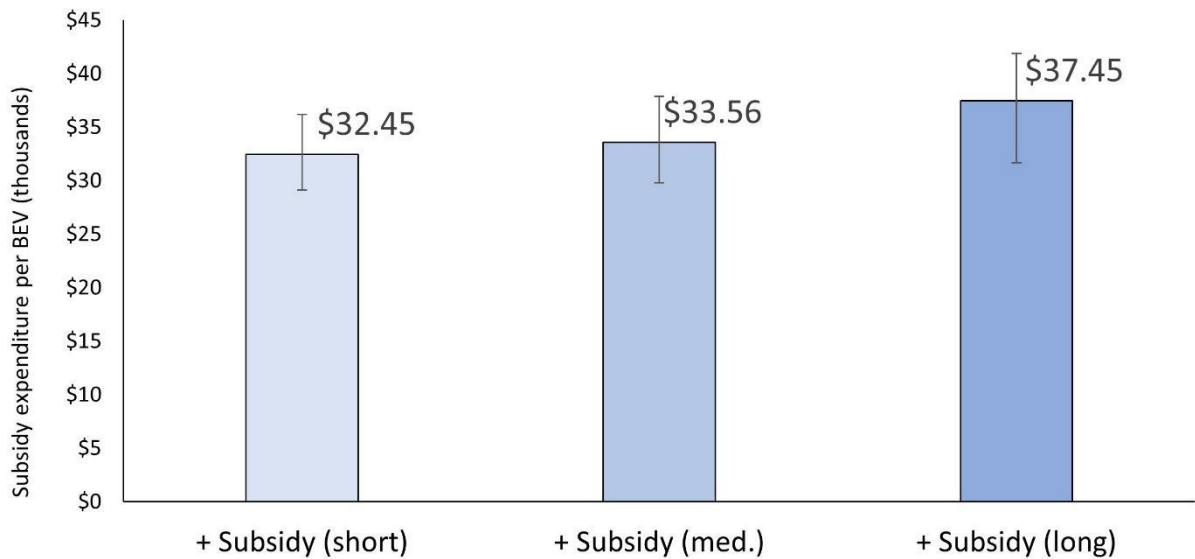
Next is government expenditure per additional tonne of CO_2e reduced, which is over $450/tonne for median scenarios in all three subsidy durations (Fig. 12). Again, these values are consistent with published literature.[12,41]

Figure 12: Subsidy expenditure per tonne reduced ($/tonne CO₂e)
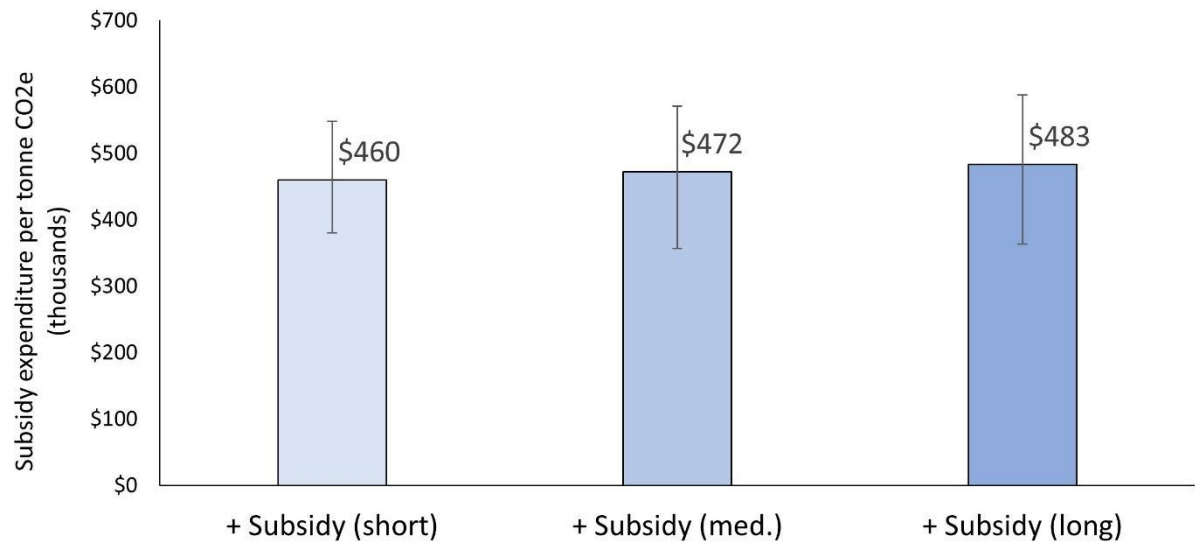
6. Summary of key findings

The selection of an ideal climate policy or policy mix requires consideration of several trade-offs. Here we provide insight regarding a subset of policy evaluation criteria, namely impacts on: ZEV sales, GHG reductions, automaker profits, ZEV prices, R&D investment, government expenditure, and the uncertainty of future estimates. Clearly the current "baseline" climate policies in Canada are not stringent enough to meet national goals for light-duty ZEV sales.

Of the two policy pathways we evaluate, **the ZEV standard offers a number of advantages compared to a large and sustained subsidy-based approach**. In particular, compared to the subsidy scenarios we examine, the ZEV standard can:

- Achieve (or come close to achieving) ZEV sales goals for 2026, 2030 and 2035, while even a sustained subsidy program falls well short of the target.
- Achieve more substantial GHG emissions reductions by 2035.
- Induce a reduction in ZEV sales prices by about 20%
- Induce a doubling in domestic automaker investment in ZEV-related R&D
- Still allow an overall increase in automaker profits from 2022 to 2035.
- Reduce the need for government expenditure on subsidies by an order of magnitude.

In contrast, the subsidy scenarios offer more benefits to automakers, including increases in automaker profits due to partial capture (13-18%) of the subsidy value. However, this rate of capture also means that not all the value of the subsidy is being passed on to consumers. Also, when the large subsidies are in place, there is a larger decrease in average ZEV sales prices of about 30% (compared to 20% for the ZEV standard).

Finally, there could be a political benefit to combining the ZEV standard and some duration of the stronger subsidies. Our modeling suggests that this policy combination can have nearly identical impacts on GHG emissions reductions, ZEV sales, and R&D investment as the ZEV standard alone. Further, the combination may reduce the loss in automaker profits from the ZEV standard. However, this policy combination will increase the requirements for government expenditure—potentially up to $80 billion if kept until 2035.

Of course, these results are specific to the assumptions of this model, and the specific policy scenarios that we simulate. Though, all results reported here are consistent across the range of optimistic and pessimistic parameters we employ in our uncertainty analyses, so we believe that the general results we highlight are fairly robust across key assumptions.

Future research could also consider the full economic costs of each policy scenarios (including social welfare), as well as political acceptability and equity impacts across policies (not studied here). Other policy scenarios (and mixes) could also be explored, including alternate designs of a ZEV standard, as well as a stringent vehicle emissions standard or feebate-based approach. The AUM simulation model could also be expanded to look at specific aspects of the auto industry in more depth, such as the luxury vehicle segment, higher resolution exploration of impacts to different vehicle classes (e.g., small car, large car, SUVs and pickup trucks), and the range of impacts to different consumer groups and to different automakers.

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