Policy Pathways to 100% Zero-Emission Vehicles by 2035 in Canada

Analysis and Research Report

January 2022

Prepared for Équiterre and the David Suzuki Foundation by

Sustainable Transportation Action Research Team (START)

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Équiterre

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One nature.

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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 modelling, consumer and citizen surveys, stakeholder interviews, media analysis and policy analysis. Our current research focus centres on four main themes:

- Markets for low-carbon transport
- Low-carbon transport fuel supply and insfrastructure
- Acceptance of alternative fuels and policy
- Modeling of low-carbon transport systems

About Équiterre

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.

About David Suzuki Foundation

is a leading Canadian environmental non-profit organization, founded in 1990. We collaborate with all people in Canada, including government and business, to conserve the environment and find solutions that will create a sustainable Canada through evidence-based research, public engagement and policy work. Our mission is to protect nature's diversity and the well-being of all life, now and for the future. Our vision is that we all act every day on the understanding that we are one with nature. Through our digital communications channels, we reach a community of more than one million people throughout Canada. We operate in English and French, with offices in Vancouver, Toronto and Montreal.

Foreword

People in Canada are waking up to the fact that our country has a vehicle emission problem. We like to drive big personal vehicles; most new purchases are sport utility vehicles (SUVs) and pickups. We are in the unenviable position of having the world's most polluting personal vehicle fleet. Despite vehicle emissions standards, carbon pricing and investments at the municipal level to expand transit and active transportation options, emissions from the transport sector have yet to start bending downwards, and the possibility of achieving the federal government's zero-emission vehicle (ZEV) targets is nowhere in sight.

Luckily, Canada has an electricity grid that is largely zero-emitting, and the forthcoming Clean Electricity Standard will accelerate replacement of fossil fuel generation with renewables. A pivotal solution in the transportation sector is to switch fuel, foregoing purchases of vehicles powered by dirty fossil fuels like gasoline and diesel in favour of those that run on clean electricity.

Yet, for far too many Canadians, few – if any – ZEVs are ready to drive off the lot. This is especially true outside of the two provinces that have a ZEV mandate, Québec and British Columbia (B.C.). Clearly, Canada has a ZEV supply problem. A recent study commissioned by Transport Canada found that 64 per cent of Canadian dealerships reported customers would have to wait between three and six months before being able to take possession of their vehicle.[1] Contrast that with the ready availability of internal combustion engine (ICE) vehicles and the pervasive advertising to encourage SUV purchases. The survey also revealed regional inequities, with Québec and B.C. having more model availability thanks to provincial ZEV mandates, while in some provinces spying a ZEV on a dealer's lot is a rare event. Furthermore, buyers in China, the European Union and even the United States (U.S.) have a greater number of ZEV models to choose from. Automakers have been reluctant to part with the profits they make selling vehicles in Canada that worsen climate change, pollute our communities and cause health impacts.

To support the federal government's ZEV commitments and climate targets, Équiterre and the David Suzuki Foundation tasked Jonn Axsen and Chandan Bhardwaj of the Sustainable Transportation Action Research Team (START) at Simon Fraser University with modelling different policies to achieve the federal ZEV target and bring down transportation sector emissions. We turned to START both for their expertise and because they are able to model both the consumer and producer sides of the new vehicle market. Their model includes behaviourally realistic representations of consumers seeking new vehicle purchases. It also represents the auto sector, including manufacturers' decisions about ZEVs under the context of climate policies, including increases in ZEV model availability, as well as investments in research and development (R&D) to reduce future ZEV costs, and to mark up the price of their ICE vehicle models, which serves to subsidize the sticker price of ZEV models and increase sale revenues. Their modelling framework allows for different trade-offs to be explored, including emissions, costs and auto manufacturing sector profits. We also asked the authors to evaluate the implications of policies that prefer battery-electric vehicles over plug-in hybrid electric vehicles, since the latter will continue to consume fossil fuel, locking in future emissions.

As part of their analysis, Axsen and Bhardwaj assess the cost effectiveness of the various regulatory options to meet Canada's ZEV targets. They also look at impacts on automaker profits and changes in consumer surplus. Some caution is necessary in interpreting these metrics. The project scope was limited, so the authors did not include in their assessment the value of health and climate benefits of reduced emissions. The evidence that vehicles with exhaust pipes harm human health due to the by-products of burning fossil fuels — such as nitrogen dioxide and ground-level ozone — is now well established.[2] For instance, a recent study found that by shifting 100 per cent of the personal vehicle fleet using the highway 401 corridor through Toronto to ZEVs, annual health

1 Dunsky Energy + Climate. Zero Emission Vehicle Availability Estimating Inventories in Canada: 2020/2021 Update. (2021).

2 Burnett, R. T., Cakmak, S. & Brook, J. R. The Effect of the Urban Ambient Air Pollution Mix on Daily Mortality Rates in 11 Canadian Cities. *Canadian Journal of Public Health* 89(3), 152–156, doi:https://doi.org/10.1007/BF03404464 (1998).

costs of $192 million would be avoided.[3] Were the study's scope expanded to include these costs, the benefits of swapping out ICE vehicles for ZEVs would be all the more evident (and the costs of mitigation would be even lower in each policy scenario).

The modelling results and analysis make two things clear. First, despite signs that auto manufacturers are beginning to step up their ZEV game and are investing in ZEV manufacturing, the modelling shows that existing policies, investments in charging infrastructure, voluntary efforts by industry, technological change and evolving consumer preferences will not make the grade: a mere 38 per cent of new vehicles sold in 2035 would be ZEVs. This would likely mean Canada would fail its climate commitments. It would also mean more local air pollution, as each additional fossil fuel–powered vehicle sold between now and 2035 locks in an extra decade or more of emissions and health impacts. Strong policies are therefore essential, combined with meaningful penalties for non-compliance. Second, the federal government has a range of options for achieving its 2025, 2030 and 2035 ZEV targets in ways that are not cost-prohibitive, allowing the automotive sector to remain profitable, but it must act quickly.

The federal government is under a lot of pressure from auto manufacturers whose main business remains selling fossil fuel–powered vehicles. This report shows that relying on existing policies and voluntary efforts by industry would leave Canada lagging far behind other advanced economies. People looking for a new vehicle in Canada need to have access to those that use 21st century technology, which protect local air quality and don't exacerbate global warming.

In publishing this study, Équiterre and the David Suzuki Foundation are mindful of the fact that zero-emitting vehicles still add to the congestion and safety issues that snarl Canadian cities and roads. While we believe ZEVs are preferable to vehicles fuelled by fossil fuels, we strongly advocate for more priority being placed on other sustainable transportation priorities, such as improving public transit, expanding active transportation networks and building complete communities that reduce car dependency and improve public health.

Andréanne Brazeau | Policy Analyst – Sustainable Mobility, Équiterre

Tom Green | Senior Climate Policy Adviser, David Suzuki Foundation

3 Shamsi, H., Munshed, M., Tran, M.-K., Lee, Y., Walker, S., The, J., Raahemifar, K. & Fowler, M. Health Cost Estimation of Traffic-Related Air Pollution and Assessing the Pollution Reduction Potential of Zero-Emission Vehicles in Toronto, Canada. *Energies* 14(16), doi: https://doi.org/10.3390/en14164956 (2021).

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List of abbreviations, acronyms and symbols

$	Canadian dollars
$/tonne	Cost-effectiveness in Canadian dollars per tonne of CO_2 abated
ASC	Alternative Specific Constant
AUM	AUtomaker-consumer Model
B.C.	British Columbia
BEV	Battery electric vehicle(s)
CFS	Clean fuel standard
CA	Recharging access
CC	Cumulative capacity
CPEVS	Canadian Plug-in Electric Vehicle Study
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent
CS	Consumer surplus
CV	Conventional vehicle(s)
CZEVS	Canadian Zero Emissions Vehicle Study
FC	Fuel costs
g	Grams
gCO_2	Grams of CO_2
gCO_2e	Grams of CO_2 equivalent
GHG	Greenhouse gas(es)
g/MJ	Carbon intensity in grams per megajoules
ICE	Internal combustion engine
IEA	International Energy Agency
km	Kilometres
KS	Knowledge stock
kWh	Kilowatt-hour
L	Litre(s)
LBD	Learning by doing
LBS	Learning by searching
LCFS	Low-carbon fuel standard
MJ	Megajoule(s)
MS	Market share
MT	Megaton(s)
MV	Model variety
PEV	Plug-in electric vehicle
PHEV	Plug-in hybrid electric vehicle
PP	Purchase parity
R	Electric driving range
R&D	Research and development
START	Sustainable Transportation Action Research Team
SUV	Sport utility vehicle
U.S.	United States
VES	Vehicle emission standards
VKT	Vehicle kilometres travelled
WTP	Willingness to pay
WTW	Well-to-wheels
ZEV	Zero-emission vehicle(s)

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Executive summary

Background

Strong policies are needed to reach Canada's goals to reduce greenhouse gas (GHG) emissions by 40 to 45 per cent by 2030 relative to 2005 levels and to reach net zero by 2050.[4] In the summer of 2021, the federal government set a target of reaching 100 per cent sales of zero-emission vehicles (ZEVs) by 2035, with an interim target of 50 per cent by 2030. Although the goal is described as a "mandatory target," it is not yet clear what policy mechanisms will be used to achieve the 2030 or 2035 targets. Achieving a 100 per cent ZEV sales goal will almost certainly require an additional strong policy or policy mix, relative to the current policies.

In this study, we explore three policy pathways for Canada to meet its 2030 and 2035 ZEV sales goals: a ZEV mandate, a vehicle emissions standard (VES) and a feebate system. We also consider three design variations of a ZEV mandate and six combinations of ZEV mandates with a VES and/or feebate. The goal is to compare these policy scenarios in terms of ZEV sales, GHG emission reductions and cost-effectiveness, the latter being measured in Canadian dollars per tonne ($/tonne) of carbon dioxide (CO_2) abated, considering impacts to consumer surplus and automaker profits.

Method

We use the AUtomaker-consumer Model (AUM) to simulate the impacts of these policies on Canada's light-duty vehicle sector from 2020 to 2035. AUM is unique in that it simulates interactions between behaviourally 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 research and development 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.

Key findings

First, we find that the current ("baseline") policies in Canada (as of September 2021) are not nearly strong enough to meet ZEV sales goals in 2030 or 2035. These sales targets can be met (or almost met) by the three "strong" policies we have examined here: a ZEV mandate, vehicle emissions standard (VES) and a feebate (Fig. ES1).

Second, we find that the baseline policies also fall short of the 2030 GHG emissions mitigation goals, even under optimistic conditions (Fig. ES2). In contrast, all of the explored policy scenarios can meet 2030 goals under median or optimistic conditions, with even deeper reductions by 2035. As one example, Fig. ES2 depicts GHG emission reductions in the baseline with the neutral ZEV mandate, and several combinations with the neutral ZEV mandate (adding a VES, feebate and VES + feebate). Generally, the GHG emission reductions of a given policy scenario are deepened when: i) the policy favours battery electric vehicles (BEVs) over plug-in hybrid electric vehicles (PHEVs) and ii) more policies are added to the mix.

4 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).

Figure ES1. ZEV market share in new vehicle sales (individual policies, median case)

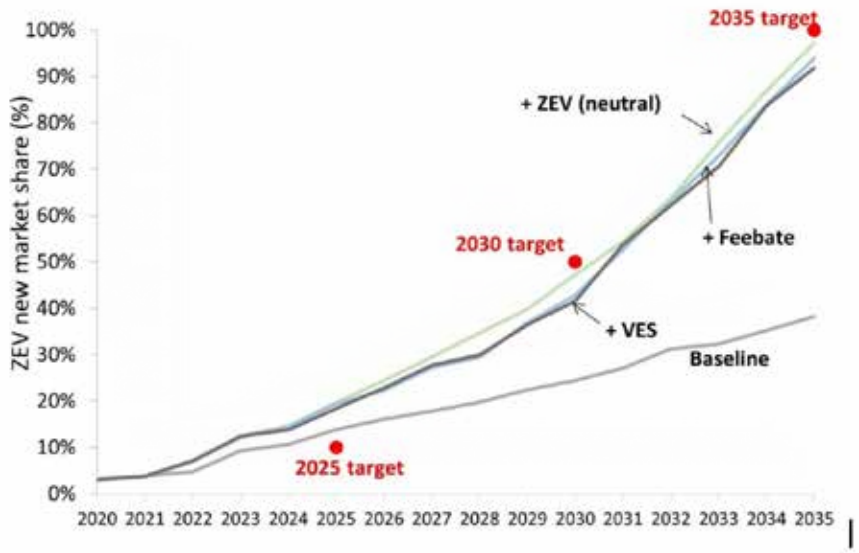
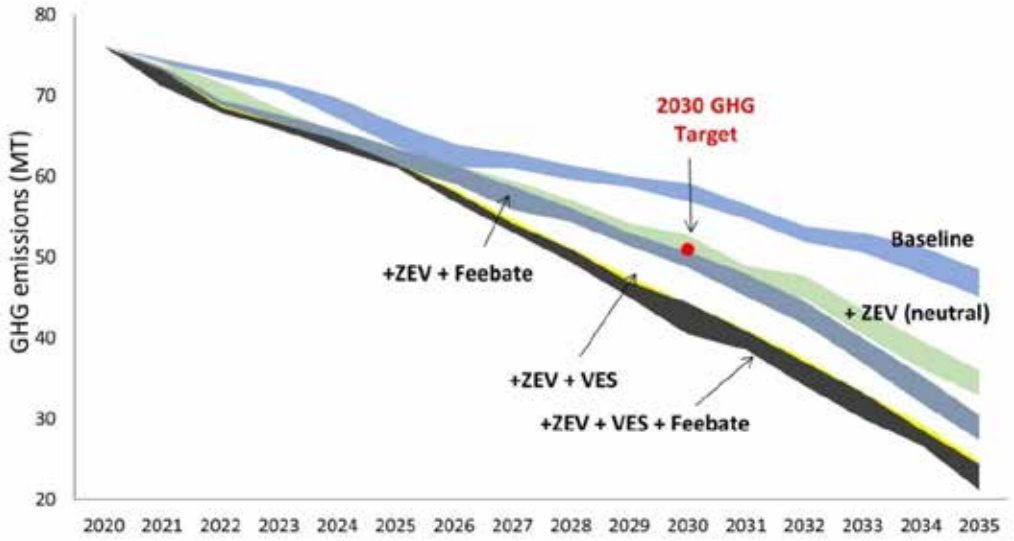


Figure ES2. GHG emissions from light-duty vehicles (neutral ZEV mandate plus policy mixes, uncertainty range includes pessimistic and optimistic parameters)

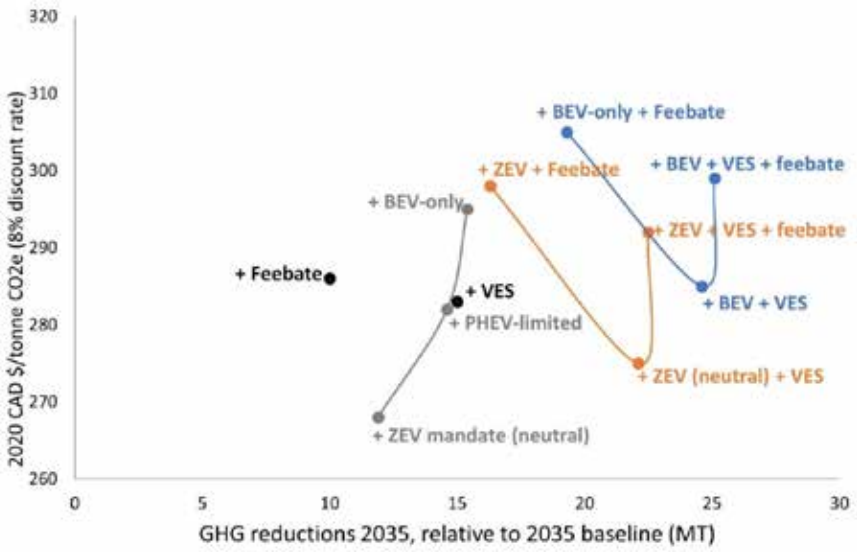


Note: The y-axis is truncated at 20 megatons (MT) for the sake of clarity.

Third, we depict the cost-effectiveness of each policy scenario relative to 2035 GHG reductions in relation to the baseline scenario in Figure ES3. We find that:

1. The neutral ZEV mandate is the **most cost-effective** way to meet the 2035 ZEV sales goal.
2. Combinations of a ZEV-mandate with a VES are also **relatively low-cost** (with further reductions in GHG emissions).
3. ZEV mandate versions that force more BEVs lead to **more GHG emissions reductions**, and are also **costlier.**
4. The feebate (alone or in combination with other policies) is **costlier** than the other policy scenarios.
5. Generally, policy scenarios tend to be **less efficient** (higher $/tonne) when:
   a. Technology options are limited (particularly a cap or ban on PHEVs);
   b. Compliance options are limited (notably a feebate); or
   c. Overall GHG emissions reductions are greater.

Figure ES3. Comparing policy cost-effectiveness ($/tonne) by 2035 GHG emissions reductions (median scenario, 8% discount rate)



Policy recommendations

The selection of an ideal 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, policy costs and the uncertainty of future estimates. Relative to a feebate, we find a ZEV mandate or VES to be more effective at GHG emissions reduction, and more cost-effective (with greater certainty). The combination of a ZEV mandate and VES is particularly promising. Using a BEV-only ZEV mandate design can produce further GHG mitigation, but at higher cost.

Future research should also consider the political acceptability of each policy, as well as potential equity impacts, which were not studied here. We also acknowledge that our cost-effectiveness calculations do not include societal co-benefits, such as potential improvements regarding air pollution, noise pollution, public health and road safety. Inclusions of these co-benefits would likely lower the costs of each policy scenario we explore here, though we expect the relative ranking of policy scenarios to remain the same.

1. Introduction

The transportation sector represented about 30 per cent of greenhouse gas emissions in Canada in 2019.[5] Between 2005 and 2019, GHG emissions in Canada's transport sector grew by 14 per cent, which represents the fastest-growing sector according to the Intergovernmental Panel on Climate Change, and by 18 per cent in the road transport sector alone.[6] Within this context, strong policies are needed to reach Canada's goals to reduce emissions by 40 to 45 per cent by 2030 (relative to 2005 levels) and to achieve net zero by 2050.[7]

To help achieve these goals, in the summer of 2021 the national government set a target of reaching 100 per cent sales of zero-emission vehicles (ZEVs) by 2035, with an interim target of 50 per cent by 2030.[8,9] Although the goal is described as a "mandatory target," it is not yet clear what policy mechanism(s) will be used to achieve the 2030 or 2035 targets. Modelling research of Canada's light-duty vehicle sector indicates that stronger policy is needed to push 2030 ZEV sales to a 30 per cent market share goal, even with the range of subsidies, pricing mechanisms and regulations currently in place.[10,11]Achieving a 100 per cent ZEV sales goal will almost certainly require the addition of a particularly strong policy or policy mix.

In this study, three policy pathways are examined for Canada to meet its 2030 and 2035 ZEV sales goals. First is a ZEV sales mandate, which requires automakers to sell a minimum market share of ZEVs, with financial penalties for non-compliance (typically in the range of $5,000 to $10,000 per vehicle). Since being introduced in California in 1990, ZEV mandates have also been implemented in several other U.S. states, as well as British Columbia (B.C.), Quebec and China. The North American ZEV mandates are now being updated to require 100 per cent sales by 2035, including plans to update the B.C. and Quebec versions. We explore the potential of a national level ZEV mandate with a similar trajectory of requirements.

5 Environment and Climate Change Canada. National Inventory Report 1990-2019: Greenhouse Gas Sources and Sinks in Canada, Canada's submission to the United Nations Framework Convention on Climate Change (2021).

6 *Ibid.*

7 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).

8 Government of Canada. Building a green economy: Government of Canada to require 100% of car and passenger truck sales be zero-emission by 2035 in Canada. (2021)

9 By ZEV, we are including plug-in hybrid vehicles (PHEVs) and battery-electric vehicles (BEVs). In most policy definitions, hydrogen fuel cell vehicles are also considered ZEVs, though we don't presently include this technology.

10 Axsen, J. & Wolinetz, M. Reaching 30% plug-in vehicle sales by 2030: Modeling incentive and sales mandate strategies in Canada. Transportation Research Part D: *Transport and Environment* 65, 596-617, doi:https://doi.org/10.1016/j.trd.2018.09.012 (2018).

11 Bhardwaj, C., Axsen, J. & McCollum, D. Simulating automakers' response to zero emissions vehicle regulation. *Transportation Research Part D: Transport and Environment* 94, 102789, doi: https://doi.org/10.1016/j.trd.2021.102789 (2021).

A second policy category is vehicle emissions standards (VES), which requires automakers to progressively reduce the average carbon intensity (gCO_2e/km) of the vehicles they sell in a given model year. A VES is more technology neutral than a ZEV mandate, as automakers can comply by improving the fuel efficiency of the internal-combustion engine vehicles they sell, as well as through fuel-switching to BEVs or PHEVs. Canada tends to follow Washington's VES policy, which under the Biden administration as of summer 2021, is set to progressively reduce the average emissions of new vehicle emissions only until 2026. Its stringency would presumably be held constant after that. As part of this report, we explore the potential for more stringent Canadian VES that could achieve the 2035 ZEV sales goal.

Third, we consider a feebate policy approach, which charges a fee for the purchase of higher-emitting vehicles and provides subsidies for low-emission vehicles and ZEVs. Such a policy can be designed to be revenue neutral, which avoids the large amount of government expenditure required for a subsidy-based approach to ZEV adoption.[12] Feebate schemes have been used in a few countries over the past decades, but typically have not been implemented with fees or subsidies that are sufficient to substantially move the vehicle fleet toward more ambitious decarbonization goals. Équiterre has recently proposed a feebate approach as a way to meet climate goals in Canada (endorsed by the David Suzuki Foundation).[13] In this report, we also consider a feebate design that could achieve 2035 ZEV sales goals.

Finally, we also consider several combinations of these policies, as history and research shows that climate policies are most often implemented in combinations, especially for the transport sector.[14] Next, we further detail our research objectives, the simulation model, our policy scenarios and results.

2. Research objectives

Our primary goal is to simulate the impacts of various policies and policy mixes on ZEV sales in Canada, relative to goals of 50 per cent sales by 2030 and 100 per cent sales by 2035. Specifically, we simulate the status quo policies in Canada as the "baseline" (current carbon pricing, ZEV purchase subsidies and regulations), and to this add:

- three ZEV sales mandate designs that vary with the type of ZEVs that are required (a "neutral" version with any mix of plug-in hybrid electric vehicles (PHEVs) or battery-electric vehicles (BEVs), one that puts a 50 per cent cap on PHEVs starting in 2030, and one that allows only BEVs starting in 2030);
- a VES that is strong enough to meet the 2035 ZEV sales target;
- a feebate system that is strong enough to meet the 2035 ZEV sales target, while being relatively revenue neutral (replacing any national and provincial subsidy schemes); and
- several combinations of the above policies (ZEV mandate, VES and/or feebate).

We also compare these policy scenarios in terms of GHG emission reductions and cost-effectiveness (which we define the same as "efficiency"). We measure cost-effectiveness through the cost in Canadian dollars ($) per tonne of CO_2 mitigated ($/tonne), considering policy impacts to both consumer utility and automaker profits.[15] In this report, our cost-effectiveness calculations do not include co-benefits, such as improvements regarding air pollution, noise pollution, public health and road safety. Inclusion of these co-benefits would likely lower the costs of each policy scenario we explore here, though we expect the relative ranking of policy scenarios to remain the same. Our results also provide details of total government expenditure for each scenario (based only on subsidy payouts, minus any collected fees in the case of a feebate system).

12 Axsen, J. & Wolinetz, M. Reaching 30% plug-in vehicle sales by 2030: Modeling incentive and sales mandate strategies in Canada. Transportation Research Part D: *Transport and Environment* 65, 596-617, doi: https://doi.org/10.1016/j.trd.2018.09.012 (2018).

13 Équiterre. The Road Ahead to Low-Carbon Mobility: A Feebate System for Canada's Light-Duty Vehicle Segment. (2020).

14 Bhardwaj, C., Axsen, J., Kern, F. & McCollum, D. Why have multiple climate policies for light-duty vehicles? Policy mix rationales, interactions and research gaps. *Transportation Research Part A: Policy and Practice* 135, 309-326 (2020).

15 Consumer utility is a measure of the welfare or well-being that a consumer derives from purchasing a good (such as a vehicle) or taking an action (driving a car or taking a bus for a trip). It can be monetized in terms of willingness-to-pay.

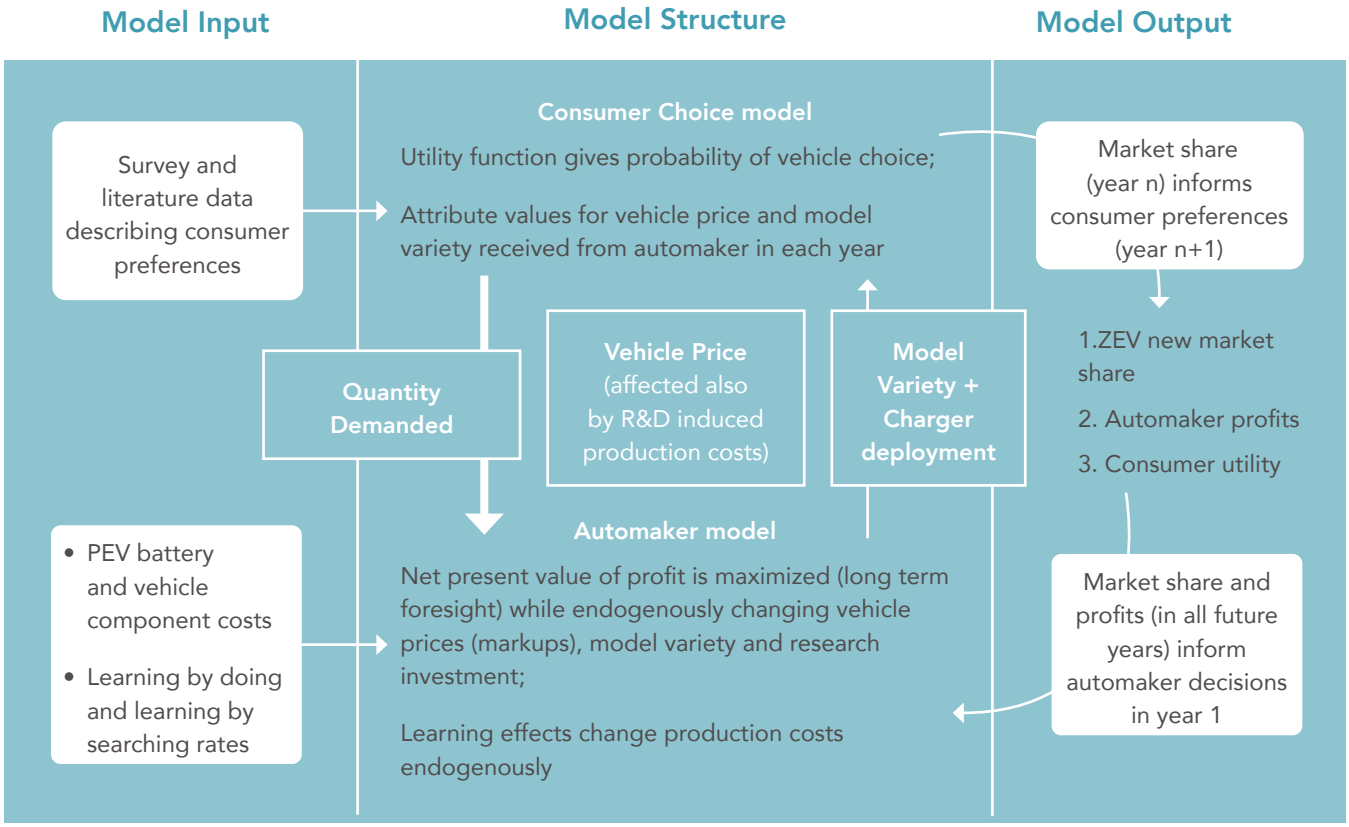
In summary, the key outputs for each policy scenario include:

- Canada's ZEV new market share for light-duty vehicles through the 2020-2035 period;
- GHG emissions from Canada's light-duty vehicles through the 2020-2035 period framed as total megatons (MT);
- Overall costs ($) of each policy scenario, consumer surplus and automaker profits, per policy, discounted to net present value using three per cent and eight per cent discount rates;
- Direct government expenditures for each scenario, understood as the total amount of money spent by government on subsidies (minus any "fees" from a feebate scheme); and
- Uncertainty analysis (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 behaviourally realistic consumers and the auto sector, as depicted in Fig. 1.[16] Specifically, the automaker (or vehicle supply) model and the consumer model interact by passing data in each one-year time period. AUM endogenously represents an aggregate automaker (instead of multiple competing automakers) that makes decisions with the goal of maximizing profit over the modelling time horizon. The automaker has multi-year foresight, and each year makes decisions about: (i) increasing ZEV model variety, (ii) intra-firm cross-price subsidies, and (iii) investing in research and development (R&D) to reduce future ZEV costs.

Figure 1. Structure of the AUM technology adoption model



16 Bhardwaj, C., Axsen, J. & McCollum, D. Simulating automakers' response to zero emissions vehicle regulation. *Transportation Research Part D: Transport and Environment* 94, 102789, doi: https://doi.org/10.1016/j.trd.2021.102789 (2021).

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. AUM also accounts for the stock of vehicles, and estimates well-to-wheels (WTW) GHG emissions for the fleet of light-duty vehicles.

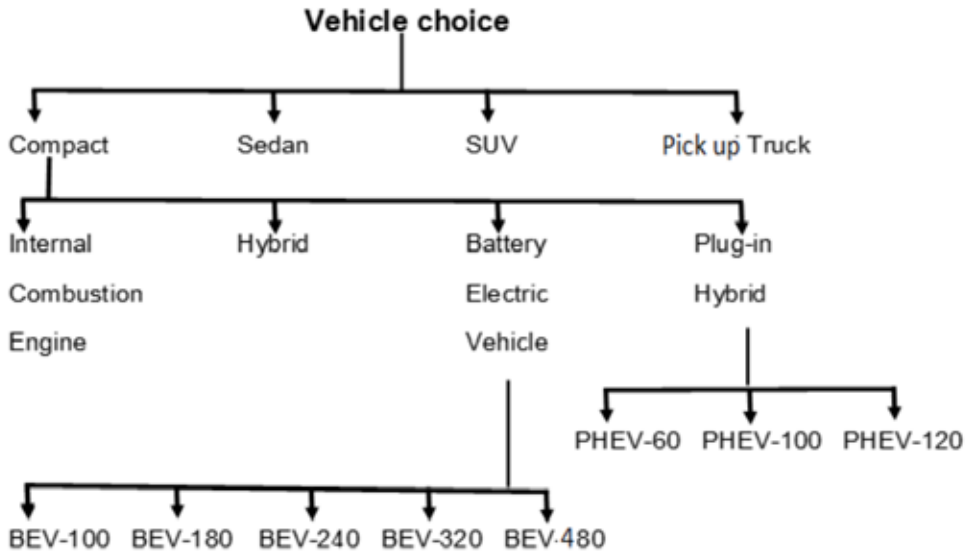
In initial studies, AUM was set up for a 2020-2030 time horizon.[17] An important part of this present study has been to extend AUM's time horizon to 2020-2035. The recalibration of the model is described in the Appendix. In the following subsections, we summarize the demand- and supply-side models, 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 shares in Canada from 2020 to 2035. Total vehicle sales are in turn affected by prices generated by the automaker model using own-price elasticities (which captures the percentage decrease in vehicle sales for every one per cent increase in average vehicle purchase price). In each year, consumers choose among available options to satisfy the demand for new vehicles, generating annual light-duty vehicle sales, which are split between four drivetrains: conventional internal combustion engine (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, sport utility vehicle [SUV] or pickup truck). At the second level, the consumer chooses from up to four different vehicle drivetrain technologies within each class: ICE, hybrid, PHEV or BEV. 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 kilometres (km), and BEVs can include ranges of 100, 180, 240, 320 and 480 kilometres.

Figure 2. Nesting of consumer choices in AUM



17 *Ibid.*

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.[18] This function is:

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

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.[19]

Model variety, expressed as the natural logarithm of the percentage of models relative to conventional vehicles, captures the idea that availability of BEV and PHEV models (n_j) is limited, affecting consumers' purchase decisions. The value of model variety is given by the logarithm of the ratio (nj/N, N is the number of conventional vehicle models).[20] For example, in 2020, only about 28 models for PHEVs exist in Canada, in comparison to about 300 for conventional vehicles. Thus, in 2020, model variety for PHEVs is about 10 per cent that of conventional vehicles.

The Alternative Specific Constant (ASC) 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:

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

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 1or 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,[21,22] and in part from international literature.[23,24,25] Consumers' base-year willingness to pay for the different attributes are listed

18 National Research Council. Transitions to alternative vehicles and fuels. (National Academies Press, 2013).

19 Hackbarth, A. & Madlener, R. Willingness-to-pay for alternative fuel vehicle characteristics: A stated choice study for Germany. *Transportation Research Part A: Policy and Practice* 85, 89-111, doi: https://doi.org/10.1016/j.tra.2015.12.005 (2016).

20 Greene, D. L. TAFV alternative fuels and vehicles choice model documentation. (Oak Ridge, TN: Oak Ridge National Laboratory, Center for Transportation Analysis, 2001).

21 Axsen, J., Bailey, J. & Castro, M. A. Preference and lifestyle heterogeneity among potential plug-in electric vehicle buyers. *Energy Economics* 50, 190-201, doi:http://dx.doi.org/10.1016/j.eneco.2015.05.003 (2015).

22 Kormos, C., Axsen, J., Long, Z. & Goldberg, S. Latent demand for zero-emissions vehicles in Canada (Part 2): Insights from a stated choice experiment. *Transportation Research Part D: Transport and Environment* 67, 685-702, doi: https://doi.org/10.1016/j.trd.2018.10.010 (2019).

23 Brand, C., Cluzel, C. & Anable, J. Modeling the uptake of plug-in vehicles in a heterogeneous car market using a consumer segmentation approach. *Transportation Research Part A: Policy and Practice* 97, 121-136, doi: https://doi.org/10.1016/j.tra.2017.01.017 (2017).

24 Dimitropoulos, A., Rietveld, P. & van Ommeren, J. N. Consumer valuation of changes in driving range: A meta-analysis. T*ransportation Research Part A: Policy and Practice* 55, 27-45, doi: https://doi.org/10.1016/j.tra.2013.08.001 (2013).

25 Ferguson, M., Mohamed, M., Higgins, C. D., Abotalebi, E. & Kanaroglou, P. How open are Canadian households to electric vehicles? A national latent class choice analysis with willingness-to-pay and metropolitan characterization. *Transportation Research Part D: Transport and Environment* 58, 208-224, doi: https://doi.org/10.1016/j.trd.2017.12.006 (2018).

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

Attribute	WTP (in $)			Range in literature ($)	Sources with comparable values of WTP
	ZEV Enthusiasts (15%)	Mainstream (50%)	Resistors (35%)		
Purchase price	-	-	-		Axsen et al. (2015), Kormos et al. (2019)
Fuel cost per $1,000 a year in fuel savings	6000	4000	2000	(1000,7000)	Brand et al. (2017)
Driving range per km increase in electric range	30	15	15	(20,200)	Ferguson et al. (2018); Dmitripoulos et al. (2013)
Model variety natural log of per 1% increase in number of PEV models, relative to CVs	3500	3500	3500	(0,10000)	Brand et al. (2017); Greene (2001)
Recharging access per 1% increase in recharging stations	550	550	550	(100,1000)	Ferguson et al. (2018); Hackbarth and Madlener (2016)
ASC in 2020					
PHEV	5000	-10000	-30000	(-50000, 8000)	
BEV	8000	-15000	-40000		
Hybrid vehicle	3000	-3000	-5000		
ASC in 2035 (optimistic, median, pessimistic)					Axsen et al. (2015), Kormos et al. (2019)
PHEV	(2275, 2030, 1800)	(0, -2400, -3050)	(0, -8954, -15k)		
BEV	(4020, 2750, 2150	(0, -3850, -5535)	(0, -13500, -20k)		
HEV	(0,0,0)	(0, 0, 0)	(0, 0, 0)		

in Table 1. CPEVS included a three-part survey completed by a representative sample of 1754 new-vehicle buying Canadian households in 2013, while CZEVS is essentially a 2017 version of this survey. They both 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.

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:

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

Where the ASC_{ok} represents the value of the *ASC* parameter at time *t=0* for technology *k; b* = constant (as used by the National Research Council).[26] As more and more ZEVs are purchased, consumer preferences for the technology are assumed to improve through increased awareness and acceptance, and improved technology performance. This "neighbour effect" and its empirical basis are presented in greater detail in Axsen et al.,[27] and have been used to represent ZEV preferences in technology adoption models such as CIMS,[28] LAVE-Trans[29] and REPAC.[30]

26 National Research Council. Transitions to alternative vehicles and fuels. (National Academies Press, 2013).

27 Axsen, J., Mountain, D. C. & Jaccard, M. Combining stated and revealed choice research to simulate the neighbor effect: The case of hybrid-electric vehicles. *Resource and Energy Economics* 31, 221-238 (2009).

28 Sykes, M. & Axsen, J. No free ride to zero-emissions: Simulating a region's need to implement its own zero-emissions vehicle (ZEV) mandate to achieve 2050 GHG targets. *Energy Policy* 110, 447-460, doi: https://doi.org/10.1016/j.enpol.2017.08.031 (2017).

29 Greene, D. L., Park, S. & Liu, C. Analyzing the transition to electric drive vehicles in the U.S. *Futures* 58, 34-52, doi: http://dx.doi.org/10.1016/j.futures.2013.07.003 (2014).

30 Wolinetz, M. & Axsen, J. How policy can build the plug-in electric vehicle market: Insights from the respondent-based preference and constraints (REPAC) model. *Technological Forecasting and Social Change* 117, 238-250 (2017).

While the data for all attributes in equation (1) for the first modelling year are 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.[31,32] First, "ZEV Enthusiasts" have a high positive valuation (negative risk aversion) for ZEVs. The "Resistors" segment favours the conventional vehicles and have a high negative valuation for ZEVs. "Mainstream," the third segment, brings together consumers who have an initial, moderate bias against ZEVs.

31 Axsen, J., Bailey, J. & Castro, M. A. Preference and lifestyle heterogeneity among potential plug-in electric vehicle buyers. *Energy Economics* 50, 190-201, doi: http://dx.doi.org/10.1016/j.eneco.2015.05.003 (2015).

32 Kormos, C., Axsen, J., Long, Z. & Goldberg, S. Latent demand for zero-emissions vehicles in Canada (Part 2): Insights from a stated choice experiment. *Transportation Research Part D: Transport and Environment* 67, 685-702, doi: https://doi.org/10.1016/j.trd.2018.10.010 (2019).

Table 2. Optimistic, median and pessimistic values for key model parameters

	2020	2030			2035			
Parameters	Values	Median	Optimistic	Pessimistic	Median	Optimistic	Pessimistic	Source
Model variety (relative to conventional vehicles)	10%	70%	90%	40%	100%	100%	60%	Authors' judgement
Recharging access (%, relative to gas stations)	10%	70%	90%	50%	100%	100%	60%	Authors' judgement
Gasoline price ($/litre [L], exclusive of carbon price)	0.83	1.02	1.18	0.7	0.65	1.15	0.51	National Energy Board (2019), U.S. Energy linformation Administration (2020), International Energy Agency (2020); Knuemo (2021)
Battery costs ($/kWh in 2020)	230	100	70	130	50	40	100	Lutsey et al. (2021)
Consumer own-price elasticity for vehicle purchase (2020-2035)	-0.6	-0.6	-0.3	-1	-0.6	-0.3	-1	Fouquet (2012); Holmgren, (2007)
Consumer elasticity for travel demand (2020-2035)	-0.2	-0.2	-0.15	-0.25	-0.2	-0.15	-0.25	Small and van Dender (2007)
Automaker rate of learning (%) (2020-2035)	8	8	10	6	8	10	6	Weiss et al. (2012), Barreto and Kypreos (2004)
Automaker discount rate (%) (2020-2035)	10	10	8	15	10	8	15	Jagannathan et al. (2016)
Vehicle stock turnover rate (%) (2020-2035)	7	7	10	5	7	10	5	National Energy Board (2019), 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 and less with impacts on specific automakers. Future extensions of AUM could explore the representation of numerous heterogeneous automakers, including the impacts of their different compliance strategies, approaches to innovation, research and development spillover effects, and trading of regulation credits (for a ZEV mandate and vehicle emissions standard that allow credit trading).

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 modelling 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:

- Increasing R&D investment (which can in part contribute to lower ZEV costs nationally over time, apart from the global exogenous decline in battery and other component costs).
- Increasing the number of ZEV models available for sale.
- Increasing charger deployment, where the automaker endogenously partly contributes to charging infrastructure. In other words, the automaker can choose to invest in added charging opportunities for ZEVs, if it helps them to comply with the policy in a cost-effective way. This effect mimics what Tesla is doing by building its own charging infrastructure.
- Changing the prices 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:

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

Where $Q_{tk}(Ptk, n_{ctk}, CA_{ctk})$ 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 set at eight per cent, which reflects the opportunity cost of capital for private firms.[33] 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}), all of which are described briefly below.

First, C_{Ptk} is the total cost of production of a vehicle technology type k in time t, given by the following equation:

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

33 Jacobsen, M. R. Evaluating US Fuel Economy Standards in a Model with Producer and Household Heterogeneity. *American Economic Journal: Economic Policy* 5, 148-187 (2013).

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*. The quadratic cost curve equation indicates the effect of diseconomies of scale.

Table 3. Exogenous parameters used in the automaker model

Parameters	Value	Source
Scaling parameter, *a* (equation 5) CVs	0.01	Authors' judgement, based on model calibration to 2018 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 2018 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)[34]
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, represented as follows:

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

We endogenously model the ZEV mandate and fuel economy standard as part of the profit function. The regulation cost associated with the ZEV mandate is then modelled as $P_{ZEV}*(\emptyset_{ZEV}*Q_{Total}-Q_{ZEV})$, where P_{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%), QTotal 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 the VES, similarly, the regulation cost is $P_{FE}*Q_k*(Z_{FE}-Z_k)$, where P_{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 third cost component in equation (4), 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:

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

34 Barreto, L. & Kypreos, S. Endogenizing R&D and market experience in the "bottom-up" energy-systems ERIS model. *Technovation* 24, 615-629 (2004).

35 *Ibid.*

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 Y_k represents the annual rate of exogenous (global) decline in the cost of production. Therefore, a vehicle's cost 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 endogenously affected 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 *KSt-1,k* (synonymous with cumulative R&D investment in Canada) achieved up to period $_{t-1}$.

Thus, while on one hand, investing in research increases the 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 Policy costs

AUM simulates the impacts of policy on both consumer utility (consumer surplus) and automaker profits. We define cumulative policy cost as the sum of changes in consumer surplus and profits under a policy scenario relative to the baseline scenario. We translate this into calculations of policy cost-effectiveness in Canadian dollars per tonne of CO_2 abated ($/tonne) by also simulating the amount of GHG emissions reduced by the policy.

The net change in consumer surplus (CS) in policy scenarios ('1') relative to the Baseline ('0') is given by:

$$\Delta CS = \frac{1}{\beta_{PP}} \left[\ln ln \left(\sum_{i=1}^{n} e^{Ui^1} \right) - \ln ln \left(\sum_{i=1}^{n} e^{Ui^0} \right) \right. \qquad (8)$$

Where U_i= utility of technology 'i' as in equation (1), and $ß_{PP}$ is the coefficient of purchase price.

Similarly, the change in profits (equation 4, in Section 3.2) can be summed to give the total private costs to automakers. The consumer surplus can be impacted through the following changes that may be induced by policy:

- Reduced total vehicle sales under the effect of policy (largely due to higher costs of ownership);
- Higher vehicle prices;
- Amenity loss, representing the loss in utility or welfare arising from consumers having to shift to a less preferable vehicle (such as shifting from trucks to cars, or from conventional vehicles to ZEVs); and
- Fuel cost savings (negative costs) that accrue to the consumer due to shifting to a more fuel-efficient vehicle under the effect of the policy.

The choice of the discount rate used in the net present value calculation can also significantly affect environmental and policy cost estimates in any modelling study. There are wide differences across the literature on the choice of discount rates. When used for private financial decisions (e.g., automakers), they tend to be higher, often around eight per cent.[36] On the other hand, to represent social decisions, some modelling studies use a lower discount rate, for example a 2.3 per cent rate by Greene et al.[37] To accommodate both perspectives, we calculate and depict overall policy costs using both an eight per cent rate and a three per cent rate.

36 Jacobsen, M. R. Evaluating US Fuel Economy Standards in a Model with Producer and Household Heterogeneity. *American Economic Journal: Economic Policy* 5, 148-187 (2013).

37 Greene, D. L., Park, S. & Liu, C. Analyzing the transition to electric drive vehicles in the U.S. *Futures* 58, 34-52, doi: http://dx.doi.org/10.1016/j.futures.2013.07.003 (2014).

3.4 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 vehicles 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:

$$\sum_{k=1}^{N} S_{t+1,k} = \sum_{k=1}^{N} S_{t,k}(1-d_{t,k}) + \sum_{k=1}^{N} Q_{t,k} \qquad (10)$$

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 baseline 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:

$$V_p = V_0 \left(\frac{fuel\ cost_p}{fuel\ cost_0}\right)^e \qquad (11)$$

Where *fuel cost*$_P$ is the fuel cost under policy, while fuel cost$_0$ is the fuel cost in the reference baseline. The baseline case vehicle use (V_0) in Canada is assumed to be 16,000 kilometres a year, based on 2020 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 based on data from the U.S. Energy Information Administration (2020) and National Energy Board (2019) — as shown in Table 4.[38,39] For PHEVs, we assume that consumers use electricity to run the PHEVs 70 per cent of the time and use gasoline for the remaining 30 per cent — which translates to a 70 per cent "utility factor." Plotz et al.[40] calculate this utility factor from real-world driving data across several countries, and find that it varies with the electric range, and across countries (e.g., for a 100-kilometre electric range PHEV, utility was about 70 per cent in Canada and Norway, but only 40 per cent in China and Netherlands). To account for uncertainty in our sensitivity analysis, we assume the utility factor is 50 per cent in the pessimistic case, and 90 per cent in the optimistic case; however, in each scenario the split is exogenous and does not respond to changes in fuel or electricity prices.

38 US EIA. Annual Energy Outlook. (2020).

39 National Energy Board. (2019).

40 Plötz, P., Moll, C., Bieker, G. & Mock, P. From lab-to-road: real-world fuel consumption and CO_2 emissions of plug-in hybrid electric vehicles. *Environmental Research Letters* 16, 054078, doi: 10.1088/1748-9326/abef8c (2021).

Table 4. Canadian vehicle energy intensity and fuel carbon intensity assumptions (illustrated for compact car vehicle class only)

Vehicle energy intensity	2020	2035	Source
CV (L/100 km)	7.55	5.73	National Energy Board (2019), U.S. Energy Information Administration (2020)
PHEV (L/100 km: 30% gasoline)	2.2	1.63	National Energy Board (2019), U.S. Energy Information Administration (2020)
PHEV (kWh/100 km: 70% electric)	0.13	0.10	National Energy Board (2019), U.S. Energy Information Administration (2020)
BEV-320 (kWh/100 km)	0.19	0.16	National Energy Board (2019)
Carbon intensity (gCO_2/MegaJoules [MJ])			
Gasoline (Default)	88.1	88.1	National Energy Board (2019); GHGenius
Gasoline (with Low Carbon 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; U.S. Energy Information Administration, 2020). Carbon intensity decreases over time under the effect of the low carbon fuel standard that is about to be imposed by the national government. 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.21

3.5 Uncertainty analysis

We follow multiple steps to explore and depict uncertainty in results, namely we (i) identify key parameters (listed below) causing most uncertainty in model outputs; (ii) depict results as uncertainty bands with pessimistic and optimistic value assumptions of the input parameters determining the boundaries of these uncertainty bands and (iii) perform sensitivity analysis to explore how variation in key parameters affects the results. 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), battery packs cost $230/kilowatt-hour (kWh) in 2020, and assume values of $40/kWh (optimistic) and $100/kWh (pessimistic) in 2035, similar to Lutsey et al.[41]

41 Lutsey, N., Cui, H. & Yu, R. Evaluating electric vehicle costs and benefits in China in the 2020–2035 time frame. (International Council for Clean Transportation, 2021).

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.[42],[43]
3. **Discount rate** used by the automaker assumes values of eight per cent (optimistic) and 15 per cent (pessimistic), corresponding to the low and high values suggested in Jagannathan et al. (2016).[44]
4. **Fuel prices** (gasoline, exclusive of any carbon price) are expected to be $0.83/litre in 2020, and assume values of $0.51/litre (pessimistic) and $1.15/litre (optimistic) in 2035. As an example, the planned Canadian carbon tax would increase these 2035 gasoline prices by 65 per cent (on average).
5. **Automaker foresight** parameter assumes two values: five years (pessimistic, representing a medium-term foresight) and 10 years (optimistic, indicating a long-term foresight), in line with previous studies.[45]
6. **Consumer preferences** represent the endogenous change of the alternative specific constant (ASC) over time (as shown in equations 1 and 3), and vary 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.
7. The exogenous global increase in **model variety** for PEVs is assumed to grow from 10 per cent (relative to model availability for conventional vehicles) in 2020, to assume values of 60 per cent (pessimistic) and 100 per cent (optimistic) in 2035.
8. **Charging access** indicates the availability of public charging infrastructure (frequency or density of chargers) relative to existing gasoline infrastructure. The value is 10 per cent in 2020, and assumes values of 60 per cent (pessimistic), 100 per cent (median) and 100 per cent (optimistic) in 2035.
9. **Domestic rate of learning,** which in AUM determines the rate at which technology improves in Canada, partly (in addition to global efforts) affects 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 cost 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 six per cent (pessimistic) and 10 per cent (optimistic), +/-25 per cent relative to the median value of eight per cent.[46] These values are constant from 2020 to 2035. The stock turnover rate indicates the exogenous rate at which existing vehicles are assumed to retire annually. We assume it varies between five per cent (pessimistic) and 10 per cent (optimistic) between 2020 and 2035.
10. **Stock turnover rate** indicates the exogenous rate at which existing vehicles are assumed to retire annually. We assume it varies between five per cent (pessimistic) and 10 per cent (optimistic) between 2020 and 2035.
11. **Vehicle kilometres travelled (VKT) elasticity of demand** determines how vehicle travel is affected in response to fuel costs and assumes values of -0.15 (optimistic) and -0.25 (pessimistic) between 2020 and 2035.
12. **Carbon intensity of gasoline (in gCO_2e/MJ)** accounts for the national clean fuel standard, and assumes values of 76 gCO_2e/MJ (optimistic) and 88 gCO_2e/MJ (pessimistic) in 2035 (Table 4).

42 Fouquet, R. Trends in income and price elasticities of transport demand (1850–2010). Energy Policy 50, 62-71, doi: http://dx.doi.org/10.1016/j.enpol.2012.03.001(2012).

43 Holmgren, J. Meta-analysis of public transport demand. *Transportation Research Part A: Policy and Practice* 41, 1021-1035, doi: https://doi.org/10.1016/j.tra.2007.06.003 (2007).

44 Jagannathan, R., Matsa, D. A., Meier, I. & Tarhan, V. Why do firms use high discount rates? *Journal of Financial Economics* 120, 445-463, doi: https://doi.org/10.1016/j.jfineco.2016.01.012 (2016).

45 Klier, T. & Linn, J. The Price of Gasoline and New Vehicle Fuel Economy: Evidence from Monthly Sales Data. *American Economic Journal: Economic Policy* 2, 134-153, doi:10.1257/pol.2.3.134 (2010).

46 Weiss, M. et al. On the electrification of road transport - Learning rates and price forecasts for hybrid-electric and battery-electric vehicles. *Energy Policy* 48, 374-393, doi: https://doi.org/10.1016/j.enpol.2012.05.038 (2012)

3.6 Validation process

Thies et al. (2016) propose validity tests to ensure that the structure of a model is an adequate representation of the underlying real-world system.[47] To validate our model, we follow a six-point validation process, building upon Thies et al.'s (2016) recommendations. The six criteria we use are:

1. The structure of the model should follow the general structure of existing simulation models of the automotive market, where such models are available and appropriate.
2. The mechanisms used within the model (e.g., learning by doing, experience spillover, purchase decisions) should be based on well-founded theories.
3. The equations connecting the model variables should be dimensionally consistent.
4. The model boundary and the aggregation level should be appropriate to address the specific research questions.
5. The model parameters should be based on empirical data, as far as possible.
6. One must ensure that the model produces plausible, realistic output behaviour, such that the outputs appear logical based on the historical record and/or an underlying theory of change for how things could be different going forward. In this regard, model comparison exercises can be useful in the model development process, helping to calibrate and validate model results and identify weaknesses and strengths of different model types.

We follow the above recommendations in our work. Table A1 in the Appendix depicts how our model performs on these validation tests.

4. Policy scenarios

Our analysis includes a total of 12 scenarios.

First is a "baseline" scenario with current policies only. These current policies include the planned carbon pricing (reaching $170/tonne in 2030), the vehicle emissions standards (VES) as recently announced by the U.S. (Environmental Protection Agency's VES), low-carbon fuel standards (B.C.'s LCFS and national CFS), charging infrastructure deployment and various purchase incentives. This scenario is detailed further in Section 4.1. All further policy scenarios include at least one more policy that is added to this baseline.

We then simulate the addition of five individual policies (one at a time): a VES, three versions of a ZEV mandate and a feebate scheme. The **VES** sets requirements (expressed in gCO_2e/km) for the level of emissions that can be released per kilometre per vehicle. We simulate a strong VES scenario that requires automakers to improve the emissions intensity (and thus reduce the energy requirement per kilometre driven) of the vehicles produced to $40gCO_2e/km$ by 2035 (tailpipe emissions, not WTW). We select this stringency as one that is approximately strong enough to meet the 2035 ZEV sales goal. We assume there are no ZEV multipliers, as these are likely to be phased out by 2022. We also assume a fine of $10/$gCO_2e$ per vehicle if the fleet-wide emissions are higher than the VES requirement. Under the VES, a BEV is treated as having 0 gCO_2e/km, while a PHEV is treated as having 70 gCO_2e/km (both being tailpipe estimates).

47 Thies, C., Kieckhäfer, K. & Spengler, T. S. Market introduction strategies for alternative powertrains in long-range passenger cars under competition. *Transportation Research Part D: Transport and Environment* 45, 4-27, doi: https://doi.org/10.1016/j.trd.2015.05.002 (2016).

The ZEV mandate requires manufacturers to sell a certain percentage of ZEVs. Following Canada's sales goals stated in 2021, we simulate a strong national ZEV mandate that requires 50 per cent of new vehicle sales to be ZEVs by 2030 and 100 per cent by 2035. For all three versions of this policy we assume a "one credit per ZEV" scheme (which is currently in place in the British Columbia) where one credit each is assigned equally to all ZEVs; a non-compliance penalty of $CDN10k/credit; and an allowance for banking of credits, where excess credits in a given year can be saved for compliance in future years. We simulate three versions of a ZEV mandate, which differ in how they treat PHEVs and BEVs (which approximate different ZEV mandate designs that are in place or being discussed in various regions):

- the "neutral" ZEV mandate allows any combination of BEVs and PHEVs;
- the "PHEV-limited" ZEV mandate limits the share of PHEVs that contribute to the ZEV requirement to 50 per cnt starting in 2030; and
- the "BEV-only" ZEV mandate that allows only BEVs to comply with the ZEV requirement starting in 2030.

The Feebate charges a tax or fee for the purchase of a conventional vehicle according to its level of emissions, and provides subsidies for the purchase of a ZEV. This feebate policy is meant to be revenue-neutral. As part of this report, though, it is only approximately revenue-neutral, since the current approach does not allow this to be exact. We select a feebate schedule that is strong enough to approximately achieve the 2030 and 2035 ZEV sales goals. Section 4.2 provides the exact schedule. Further, in the feebate-only scenario and any policy mix that includes a feebate, the national and provincial ZEV subsidies are fully removed, starting in 2022.

We also simulate six policy mixes. These consist of three policies with the neutral ZEV mandate (+VES, +feebate, and +VES+feebate), and three policies with the BEV-only ZEV mandate (+VES, +feebate, and +VES+feebate).

4.1 Baseline scenario details

Here we provide further details of the policies we model in the "baseline" scenario. We will model current policies as follows:

1. **Carbon pricing:** Following the national pricing plan, a national carbon tax increases from $50/tonne in 2020 to $170 in 2030.[48]
2. **National Clean Fuel Standard (CFS):** is modelled to reduce the carbon intensity (g/MJ) of liquid fuels by 13 per cent by 2030, moving from 90.4 g/MJ to 81.0 g/MJ.
3. **Low-carbon fuel standard (LCFS):** The carbon intensity of liquid fuels in B.C. is further reduced by the province's LCFS (for vehicles in this province), working with the CFS to reach 80.5 g/MJ by 2030.
4. **ZEV mandate:** We account for existing ZEV mandates in British Columbia and Quebec as follows (as of September 2021):
   - BC: ZEVs make up 10 per cent of sales by 2025, 30 per cent by 2030, 65 per cent by 2035 and 100 per cent by 2040.[49]
   - Quebec: ZEVs make up 12.5 per cent of sales by 2025, 65 per cent by 2030 and 100 per cent by 2035.
5. **Purchase incentives:** We account for all national and provincial ZEV subsidies, separated for BEVs (Table 5) and PHEVs (Table 6). We use the magnitudes announced for each region, and estimate duration based on announced funds. We also include a four-year extension to the national BEV/PHEV subsidies based on the Liberal government platform in September 2021. Note that because AUM is currently set up to model Canada as a whole (not individual provinces), the ZEV incentives are calculated using a sales-weighted average for Canada (as shown in Tables 5 and 6).

48 Carbon taxes increase fuel costs for consumers, which impacts vehicle purchase decisions, and also reduces vehicle travel (VKT) while reducing overall new vehicle sales. Automaker decisions are impacted indirectly, in as much as it affects consumers' choice of different drivetrain or vehicle size.

49 After this modelling analysis was completed, British Columbia announced that it would set a ZEV requirement of 90 per cent sales by 2030. Inclusion of this updated requirement would not substantively change the results of this analysis.

Table 5. Baseline subsidies for BEVs

BEVs	2020	2021	2022	2023	2024	2025	2026	2027-30
Canada	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000	
B.C.	$3,000	$3,000	$3,000	$3,000	$3,000			
QC	$8,000	$8,000	$8,000	$8,000	$8,000	$8,000	$8,000	
Nova Scotia	$3,000	$3,000	$3,000	$3,000	$3,000			
PEI	$3,750	$3,750	$3,750					
NFL	$2,500	$2,500	$2,500					
Yukon	$4,000	$4,000	$4,000	$4,000				
Sales-weighted total	$7,425	$7,425	$7,425	$7,364	$7,347	$6,938	$6,938	$0

Table 6. Baseline subsidies for PHEVs

BEVs	2020	2021	2022	2023	2024	2025	2026	2027-30
Canada	$2,500	$2,500	$2,500	$2,500	$2,500	$2,500	$2,500	
BC	$1,500	$1,500	$1,500	$1,500	$1,500			
QC	$4000	$4000	$4000	$4000	$4000	$4,000	$4,000	
Nova Scotia	$2,000	$2,000	$2,000	$2,000	$2,000			
PEI	$3,750	$3,750	$3,750					
NFL	$2,500	$2,500	$2,500					
Yukon	$4,000	$4,000	$4,000	$4,000	$4,000			
Sales-weighted total	$3,770	$3,770	$3,770	$3,709	$3,693	$3,468	$3,468	$0

6. **ZEV charging infrastructure deployment:** We assume that PHEV and BEV recharging availability increases from 10 per cent in 2020 to 70 per cent of light-duty vehicle buyers by 2030 (relative to gasoline refuelling infrastructure, which is 100 per cent), and 100 per cent of car buyers by 2035 (which is equivalent to gasoline fuelling infrastructure). In the pessimistic parameter scenario, charging access only reaches 60 per cent of consumers by 2035. The treatment of charging access is not currently differentiated between home or public (non-home) chargers. We assume that refuelling access for conventional gasoline vehicles is 100 per cent.

7. **Vehicle emissions standard:** The baseline VES follows Biden's recently announced policy in the U.S. We assume there are no "multipliers" with the expectation that multipliers will be phased out in the Canada version. The schedule is as follows (where the 2026 values are held constant until the end of the modeling period, 2035):

- 2020: 140 gCO_2e/km
- 2021: 134 gCO_2e/km
- 2022: 132 gCO_2e/km (1.5% reduction from previous year)
- 2023: 119 gCO_2e/km (10% reduction from previous year)
- 2024: 113 gCO_2e/km (5% reduction from previous year)
- 2025: 107 gCO_2e/km (5% reduction from previous year)
- 2026-2035: 102 gCO_2e/km (5% reduction from previous year)

4.2 Feebate details

We determined a feebate structure that would approximately achieve the 2035 100 per cent ZEV sales goal, while maintaining a rate close to neutrality. In this scenario, fees on conventional vehicles and hybrids increase annually at about 10 per cent, and rebates for PHEVs and BEVs decrease at the same rate (Table 7). When modelling this scenario, we assume other subsidies (national and provincial) are absent.

Although this feebate scenario is approximately revenue-neutral when the feebate is modelled only in combination with the baseline policies, this revenue neutrality is not achieved in policy mix scenarios. Generally, when the feebate is added to other strong policies, ZEV new market share is further increased, leading to more subsidy payout than fees collected for the government. Such a result is a product of our modelling approach, and could surely be avoided through a feebate scheme that is designed to adjust fees and subsidy values each year in order to achieve revenue neutrality.

5. Results

We summarize our modelling results by first presenting our uncertainty analysis. We then depict results on effectiveness (ZEV sales and GHG mitigation) for policy scenarios, broken into four clusters: individual policies, ZEV mandate design variations, policy mixes with a neutral ZEV mandate, and policy mixes with a BEV-only mandate. The final section summarizes key findings from each scenario, as well as policy costs and government expenditure for each scenario.

5.1 Uncertainty analysis

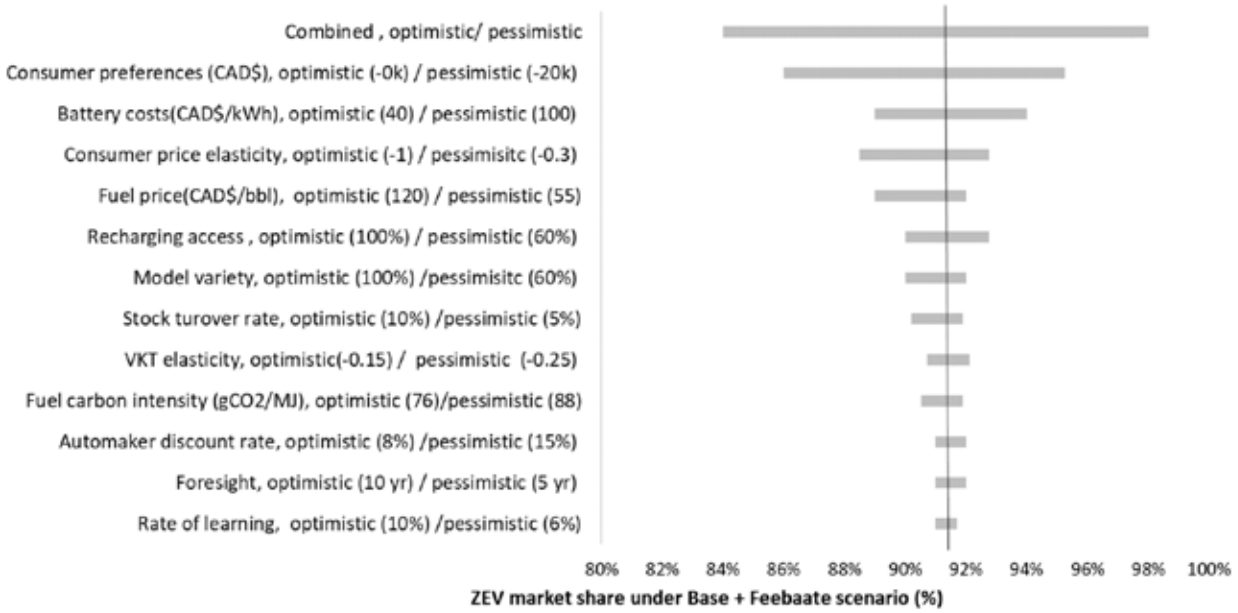
As described in Section 3, there is inherent uncertainty in this modelling exercise, as there is in any study that simulates vehicle sales more than a decade into the future. We account for uncertainty by conducting a sensitivity analysis. As noted in Section 3.5, for key parameters we select median values from the literature, as well as "optimistic" and "pessimist" values. These terms are selected in relation to ZEV market share; optimistic parameters lead to higher ZEV market share, while pessimistic parameters lead to lower ZEV market share. In sensitivity analysis, we identify a key result or model output, and calculate how that result changes with changes in each of those uncertain parameters, one at a time. This process helps us to identify key uncertainties in the model, which aids in interpretation of results while identifying important directions for future research.

Fig. 3 provides a representative example using the median simulation of 2035 ZEV market share, using one particular policy scenario: "Baseline + Feebate." While the median scenario simulates a market share of 92 per cent, the combination of optimistic parameters leads to a ZEV market share of 98 per cent, and the combination of pessimistic parameters reduces market share to 84 per cent. Figure 2 is known as a "tornado diagram," as it starts with the most sensitive parameters at the top, and moving downward the horizontal lines represent parameters that the model output is less sensitive to.

Table 7. Subsidy/fee structure for the feebate scenario (approximately revenue neutral)

Vehicle class	Drivetrain	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Compact car	CV	$1,149	$1,264	$1,390	$1,529	$1,682	$1,851	$2,036	$2,240	$2,464	$2,701	$2,981	$3,279	$3,607	$3,968
	Hybrid	$710	$789	$876	$974	$1,082	$1,202	$1,336	$1,484	$1,649	$1,832	$2,036	$2,262	$2,436	$2,997
	PHEV	-$7,024	-$6,386	-$5,805	-$5,277	-$4,798	-$4,361	-$3,965	-$3,604	-$3,277	-$2,979	-$2,708	-$2,474	-$2,238	-$2,034
	BEV	-$13,636	-$12,396	-$11,269	-$10,245	-$9,513	-$8,467	-$7,697	-$6,997	-$6,361	-$5,783	-$5,257	-$4,776	-$4,344	-$3,949
Sedan car	CV	$1,573	$1,730	$1,903	$2,096	$2,303	$2,533	$2,786	$3,065	$3,371	$3,709	$4,079	$4,487	$4,936	$5,430
	Hybrid	$1,149	$1,264	$1,390	$1,529	$1,682	$1,851	$2,036	$2,240	$2,464	$2,710	$2,981	$3,379	$3,797	$3,968
	PHEV	-$7,024	-$6,386	-$5,805	-$5,277	-$4,798	-$4,361	-$3,965	-$3,604	-$3,277	-$2,979	-$2,708	-$2,474	-$2,238	-$2,034
	BEV	-$13,636	-$12,396	-$11,269	-$10,245	-$9,513	-$8,467	-$7,697	-$6,997	-$6,361	-$5,783	-$5,257	-$4,776	-$4,344	-$3,949
SUV (Van/ truck)	CV	$1,815	$1,996	$2,196	$2,415	$2,657	$2,923	$3,215	$3,536	$3,890	$4,279	$4,707	$5,178	$5,696	$6,265
	Hybrid	$1,210	$1,331	$1,464	$1,610	$1,771	$1,948	$2,143	$2,357	$2,593	$2,853	$3,138	$3,452	$3,815	$4,177
	PHEV	-$7,024	-$6,386	-$5,805	-$5,277	-$4,798	-$4,361	-$3,965	-$3,604	-$3,277	-$2,979	-$2,708	-$2,474	-$2,238	-$2,034
	BEV	-$13,636	-$12,396	-$11,269	-$10,245	-$9,513	-$8,467	-$7,697	-$6,997	-$6,361	-$5,783	-$5,257	-$4,776	-$4,344	-$3,949
Pickup truck	CV	$4,840	$5,324	$5,856	$6,442	$7,086	$7,794	$8,574	$9,431	$10,387	$11,412	$12,353	$13,809	$15,190	$16,708
	Hybrid	$2,420	$2,620	$2,934	$3,221	$3,453	$3,897	$4,287	$4,715	$5,187	$5,706	$6,276	$6,904	$7,595	$8,354
	PHEV	-$7,024	-$6,386	-$5,805	-$5,277	-$4,798	-$4,361	-$3,965	-$3,604	-$3,277	-$2,979	-$2,708	-$2,474	-$2,238	-$2,034
	BEV	-$13,636	-$12,396	-$11,269	-$10,245	-$9,513	-$8,467	-$7,697	-$6,997	-$6,361	-$5,783	-$5,257	-$4,776	-$4,344	-$3,949

Figure 3. Sensitivity analysis (ZEV market share in 2035, "baseline + feebate scenario)



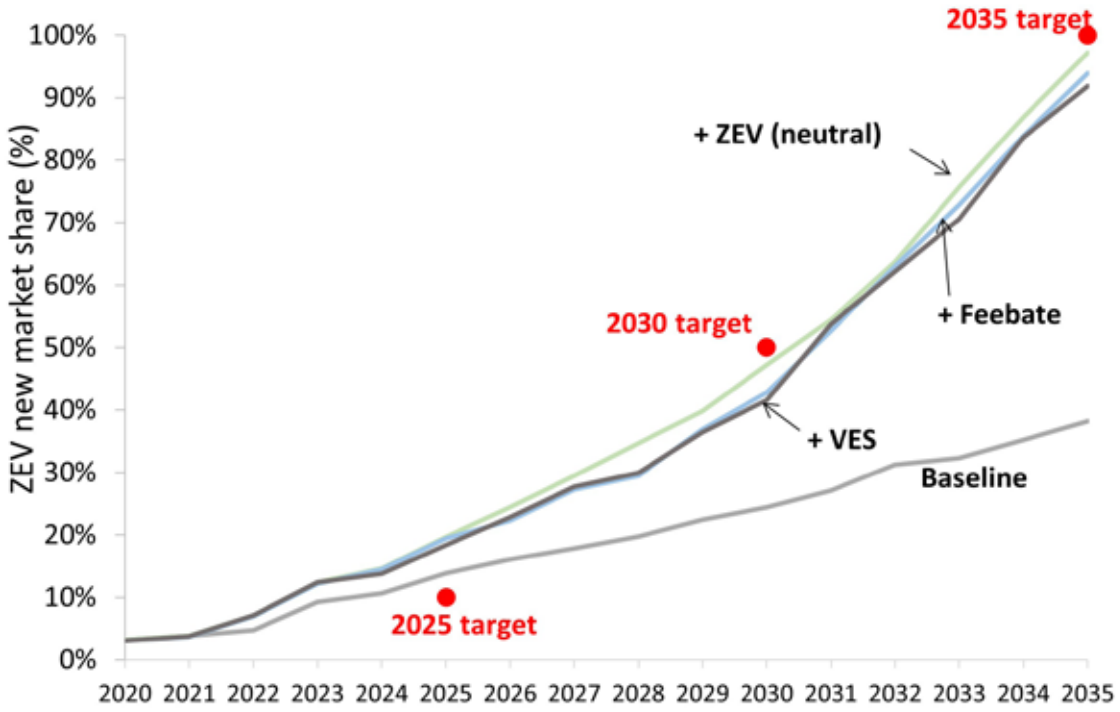
The model results are most sensitive to changes in consumer preference parameter, which we measure as a change in how consumers in the "resistor" segment value BEVs (the alternative specific constant or ASC in Equation 1) in 2035. Changing that parameter alone can change ZEV market share in 2035 from 86 per cent to 95 per cent. The next most influential parameter is battery costs in 2035 (moving market share from 89 per cent to 94 per cent), followed by consumer own-price elasticity for vehicle sales (89 per cent to 93 per cent), fuel prices (89 per cent to 92 per cent), and recharging access in 2035 (90 per cent to 93 per cent).

In the following subsections we continue to communicate this uncertainty by showing the range of results in figures depicting ZEV market share and GHG emissions. The high lines for ZEV market share (and low lines for GHG emissions) represent all 12 uncertain variables at their "optimistic" setting, while the low lines for ZEV market share (and high lines for GHG emissions) result from "pessimistic" settings.

5.2 Comparing individual policies (neutral ZEV mandate, VES and feebate)

The section presents results for the baseline and individual policy scenarios. Fig. 4 depicts the ZEV new market share over time (including both BEVs and PHEVs, as is done throughout this report) for the median parameter levels. Under the baseline policy scenario, the median simulation of ZEV sales is 24 per cent in 2030 (well below the 50 per cent target) and 38 per cent in 2035 (well below the 100 per cent target).

Figure 4. ZEV market share in new vehicle sales (individual policies, median case)

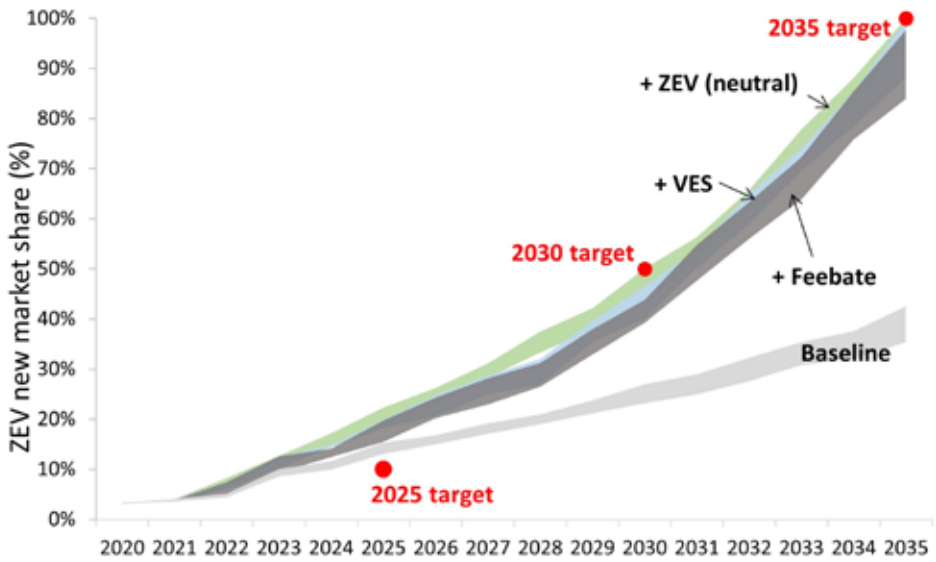


In contrast, each of the three individual policy scenarios (neutral ZEV mandate, VES and feebate) comes close to meeting 2030 and 2035 sales targets by design, though they all fall short of both targets by two to eight percentage points in the median scenario. The slight shortfall of results of the feebate and VES are driven by scenario design — a stronger VES or stronger feebate program (larger fees and subsidies) could move market share further toward the target.

The neutral ZEV mandate is the only policy to specifically push automakers to comply with the ZEV sales goals (with penalty for non-compliance). This scenario can fall short of the goals by about three percentage points for two possible reasons: i) automakers are banking credits from over-compliance in earlier years to comply with 2030 and 2035 requirements, and/or ii) automakers choose to pay the penalty of $10,000/vehicle for non-compliance, as this is cheaper than further subsidizing their ZEVs (or following other compliance pathways) to the amount needed to reach this last few per cent of the market.

In this case, most of the effect is from non-compliance. 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 the 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, or choosing to pay fines for a small portion of non-complying sales relative to the requirement.

Figure 5. ZEV market share in new vehicle sales (individual policies, uncertainty range)

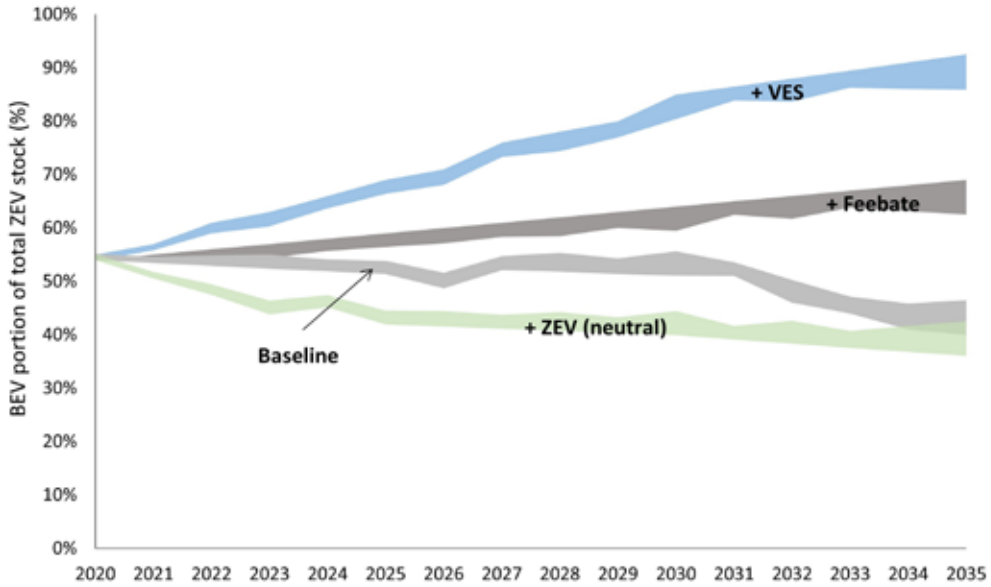


The results are largely consistent with the median estimates (Fig. 4), showing that the baseline policies come nowhere near the ZEV sales targets — even under optimistic conditions, the 2035 ZEV market share does not exceed 43 per cent. We again see that the three individual policies come close to the targets. Full compliance with the ZEV targets only occurs under optimistic conditions in a few cases: the ZEV mandate achieves the 2030 and 2035 targets, and the VES achieves the 2035 target.

In comparing the range of uncertain outcomes, the ZEV mandate leads to a narrower, relatively more certain range of outcomes in 2035 (96 per cent to 100 per cent), while the feebate comes with the largest range of uncertainty (84 per cent to 98 per cent). It is for this reason that the uncertainty analysis in Section 5.1 focused on the feebate scenario. The relative certainty of each scenario (whether it is a wide or narrow range) may also be of interest to policymakers, where a narrower range (or more certain outcome) that is closer to the goal is more desirable than a wider range (or less certain outcome).

Fig. 6 displays the proportion of BEVs in the total ZEV sales in each year for the different policy scenarios. Under the baseline scenario, BEVs make up just over 50 per cent of the total ZEV sales in the first decade (51 to 56 per cent), but this share falls to 40 to 47 per cent after 2030. This is largely due to the removal of national and provincial subsidies that favour BEVs (Section 4.1), and due to our median case assumptions that the PHEVs are the preferred drivetrain technology for a majority of Canadian consumers up to 2035. In contrast, the proportion of BEV sales increase over time for the feebate and VES by design. The feebate system gives increasingly higher support for BEVs over time, while the VES gives more credit to BEVs (which are rated as being 0 gCO_2e/km) to achieve increasingly higher fleetwide standards (<40g/km in 2035).

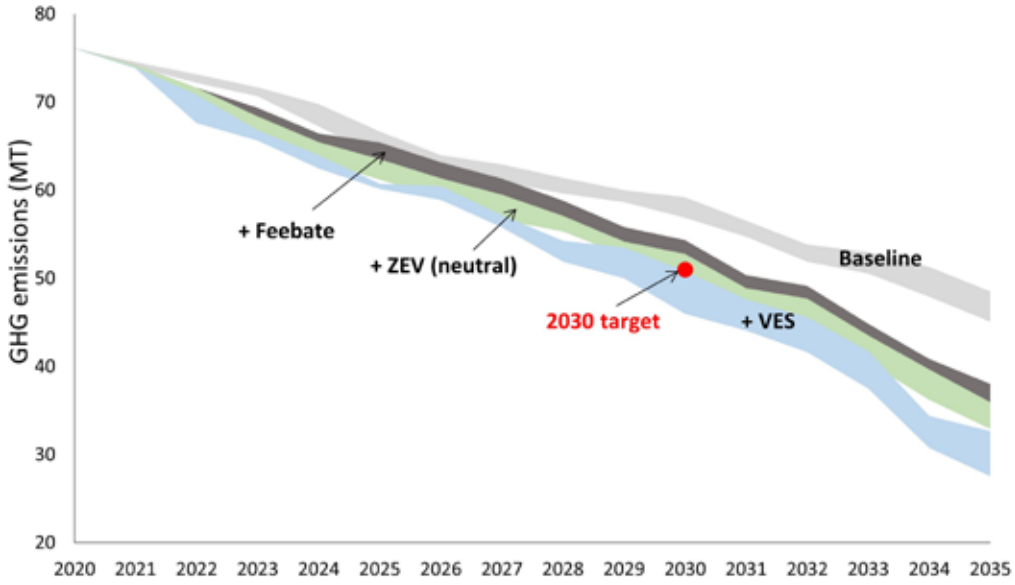
Figure 6. Percentage of BEVs in ZEV sales for each sales year (individual policies, uncertainty range)



The BEV proportion is lowest under the neutral ZEV mandate, reaching 36 to 43 per cent in 2035. The explanation is that this version of the ZEV mandate provides equal credits for PHEVs and BEVs, with no cap on PHEVs. Consumer preferences are generally higher for PHEVs (as summarized in Section 3.1), so automakers find it cheaper to sell more PHEVs than to sell more BEVs. The next section explores how these results change with variations in the design of a ZEV mandate.

Fig. 7 depicts the total GHG emissions from the stock of light-duty vehicles from 2020 to 2035 under each policy scenario. To start, the baseline policy scenario falls short of the assumed 2030 goal of 51 MT (40 per cent below 2005 levels) by six to nine MT, even under optimistic conditions. All three policy scenarios include the target within their uncertainty range: 51 to 53 MT for the ZEV mandate, 46 to 51 MT for the VES and 48 to 54 MT with the feebate.

Figure 7. GHG emissions from light-duty vehicles (individual policies, uncertainty range)



Note: The y-axis is truncated at 20MT for the sake of clarity.

Under the stringencies we have selected for these simulations, the strengthened vehicle emissions standard (VES) provides substantially more GHG reductions in 2035 than the feebate or neutral ZEV mandate. Differences in GHG impacts largely correspond with: i) the total ZEV sales to that point, and ii) differences in the proportion of BEVs in those ZEV sales (in Fig. 6). The VES performs better than the ZEV mandate in this regard because PHEVs constitute a larger proportion of total sales in the ZEV mandate. Although the feebate offers a higher proportion of BEVs than the ZEV mandate, it also has fewer ZEV sales, leading to slightly fewer GHG reductions under the median case assumptions.

5.3 Comparing ZEV mandate designs

This section summarizes results for three versions of the ZEV mandate: a design that is neutral in relation to PHEVs versus BEVs (as shown in the previous section), a design that limits the proportion of PHEVs to 50 per cent of ZEV market share starting in 2030 ("PHEV limited"), and a design that only allows BEVs starting in 2030 ("BEV-only"). All three ZEV mandates have similar ZEV sales trajectories for their median case (Fig. 8), and identical uncertainty ranges of 96 to 100 per cent for 2035 sales (Fig. 9).

Figure 8. ZEV market share in new vehicle sales (ZEV mandate variations, median case)

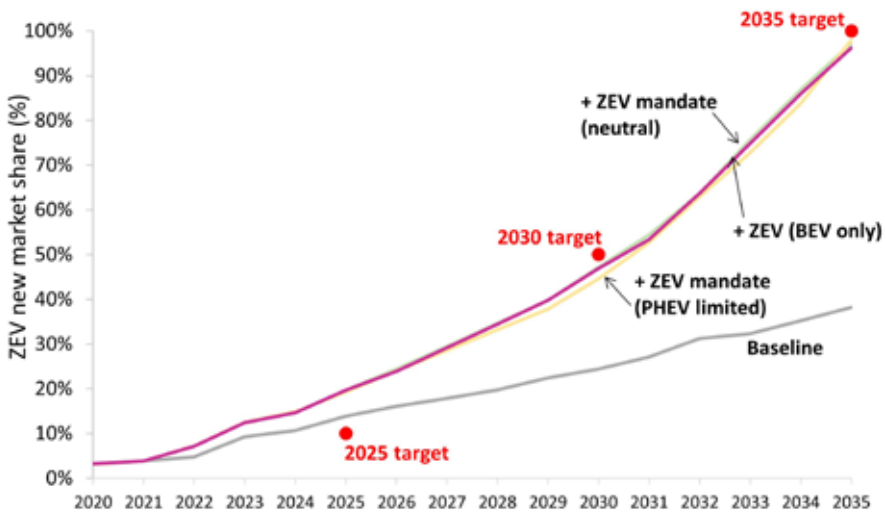


Figure 9. ZEV market share in new vehicle sales (ZEV mandate variations, uncertainty range)

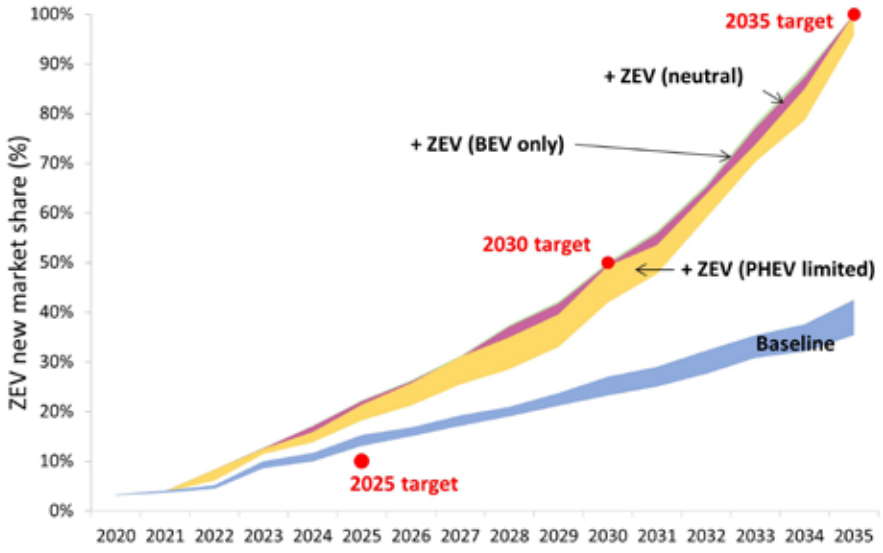
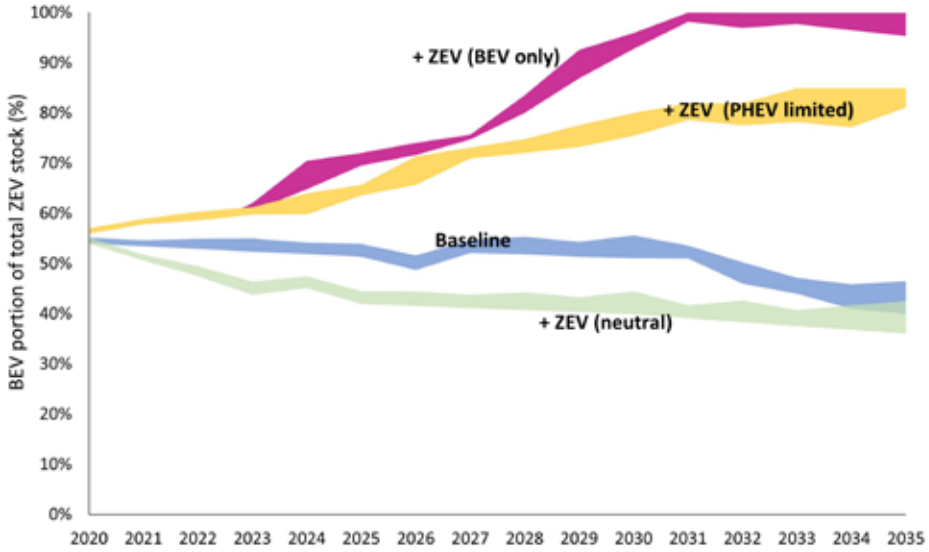


Fig. 10 portrays the main difference between ZEV mandate designs: the trajectory of the share of BEVs among ZEV sales. As already shown in Section 5.2, the neutral ZEV mandate leads to 36 to 43 per cent of ZEVs being BEVs in 2035. The PHEV-limited ZEV mandate gradually moves up to BEVs making up over 80 per cent of ZEV sales in 2035. Finally, the BEV-only mandate moves up toward 100 per cent, though in pessimistic cases the 2035 BEV share is 95 per cent (meaning that some PHEVs are being sold, despite not earning credit in the ZEV mandate).

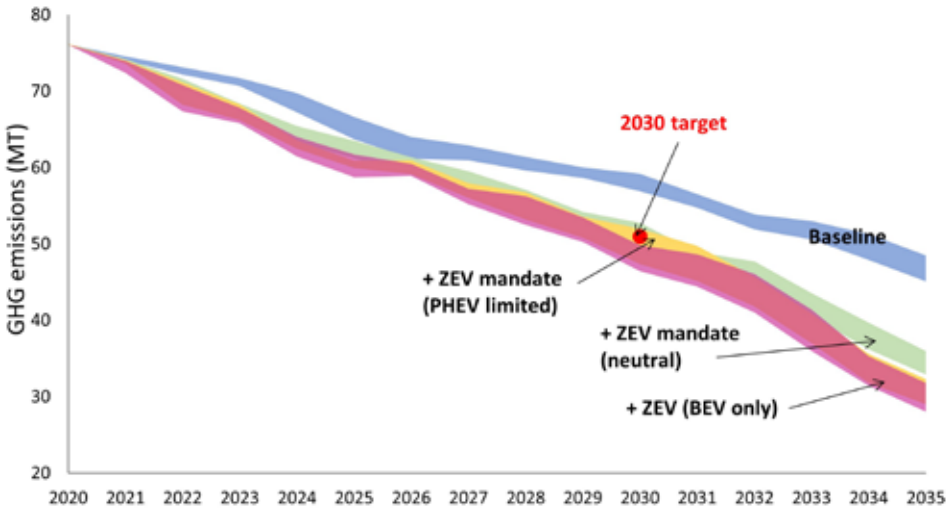
Figure 10. Percentage of BEVs in ZEV sales for each sales year (ZEV mandate variations, uncertainty range)



Overcompliance in the PHEV-limited scenario (where BEVs make up more than 50 per cent) is largely a function of the perfect foresight (up to 2035) for the automakers. In general, consumers have higher preference for PHEVs, as in the baseline scenario. However, once a threshold market share of around 60 per cent BEVs (out of total ZEVs) is reached, consumers have a higher preference for BEVs start to improve sharply. With BEVs already cheaper than PHEVs since late 2020, improved consumer preferences for BEVs make it a preferred choice for an increasingly larger share of consumers. Since the automaker in our model has this foresight (which may not be available in the real world), the automaker pushes more BEVs sooner, starting as early as 2021, so that due to the endogenous learning in the model, BEV consumer preferences improve to a level comparable to PHEVs by 2030. At this stage, a significant proportion of consumers will buy BEVs even without cross-price subsidization, leading to overcompliance.

Fig. 11 translates these results into GHG emission reductions. All three versions can achieve the assumed 2030 GHG emissions target, and continue to outperform the baseline in 2035. In that year, the BEV-only and PHEV-limited ZEV mandates have similar GHG impacts, and both lead to more reductions than the neutral ZEV mandate. As explained earlier, policies with greater BEV uptake result in greater GHG emissions reductions (all else held constant).

Figure 11. GHG emission reductions from light-duty vehicles (ZEV mandate variations, uncertainty range)



Note: The y-axis is truncated at 20MT for the sake of clarity.

5.4 Comparing policy mixes (with neutral ZEV mandate)

To aid the policy mix comparison, we split up the policy mixes into those with a neutral ZEV mandate, shown in this section, and those with a BEV-only ZEV mandate, shown in the next section.

Figs. 12 and 13 show the ZEV market share impacts of a neutral ZEV mandate with a feebate, a VES and a feebate + VES. The addition of policies to the mix generally leads to higher ZEV sales (particularly from 2028 to 2034), and every combination exceeds 2030 sales targets (even under pessimistic conditions). Interestingly, these impacts lead to overcompliance with a ZEV mandate in these initial years, which is again driven by the automaker strategy (with perfect foresight) to seek to improve preferences for ZEVs, and earn a full markup for ZEVs in future years. The policy mixes achieve the 100 per cent target with high levels of certainty, with a market share over 97 per cent even under pessimistic cases.

In terms of combinations, the strengthened VES leads to more of a sales boost than the implementation of a feebate system. The three-way combination of a ZEV mandate, VES and feebate does not have much more impact than the ZEV mandate and VES combined.

Figure 12. ZEV market share in new vehicle sales (policy mixes with neutral ZEV mandate, median case)

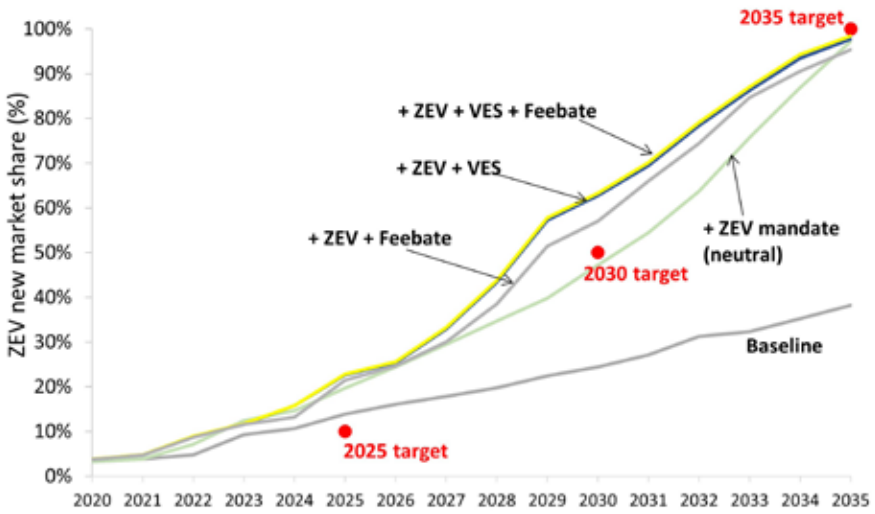
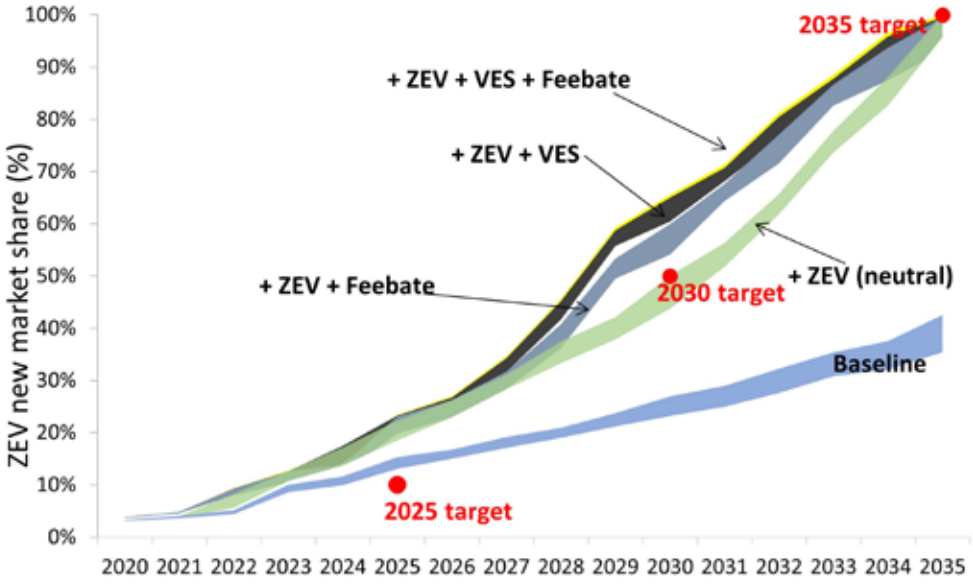
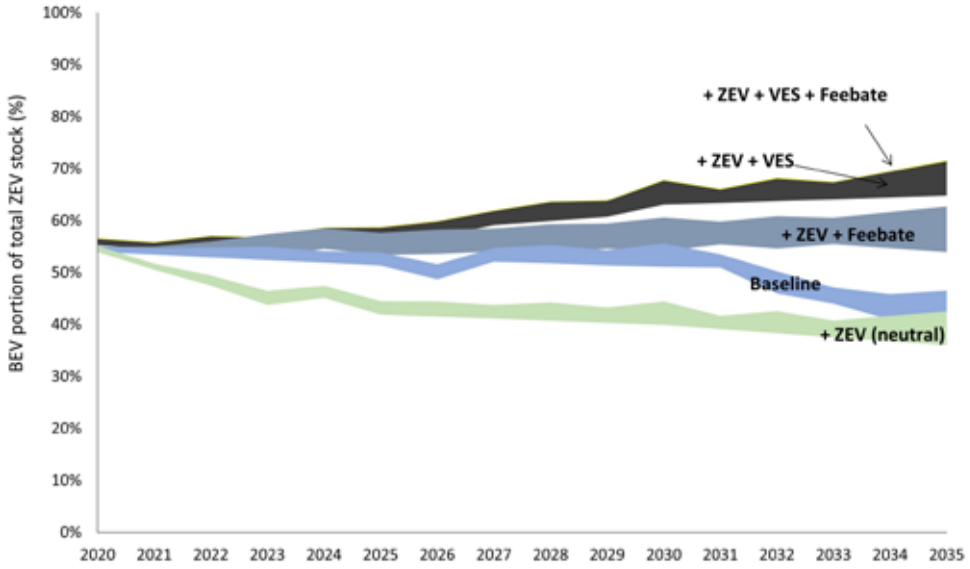


Figure 13. ZEV market share in new vehicle sales (policy mixes with neutral ZEV mandate, uncertainty range)



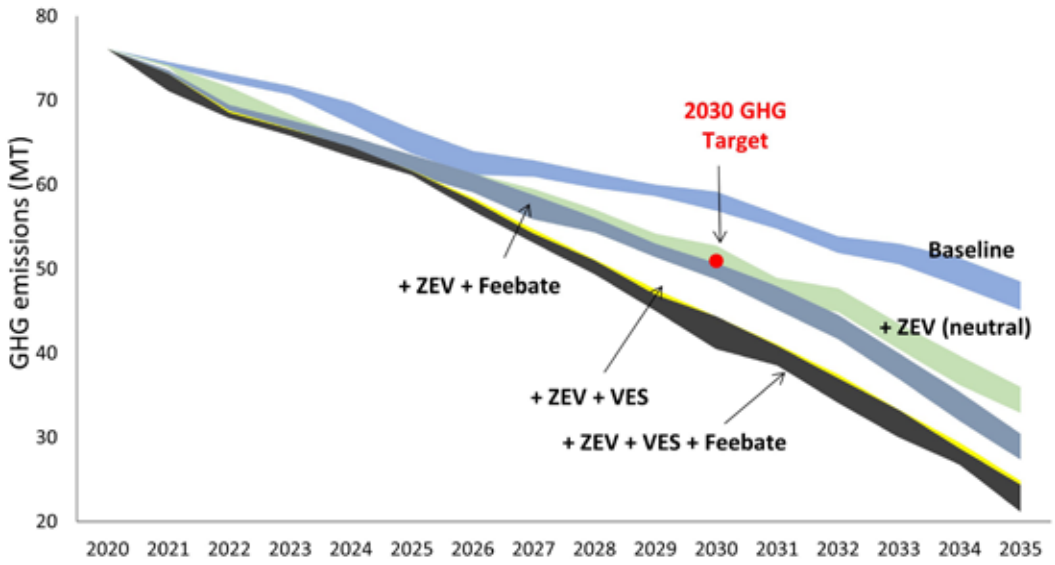
Because both the VES and feebate policies favour BEVs over PHEVs (as described earlier), their inclusion in a policy mix leads to a higher share of BEVs than the neutral ZEV mandate alone (Fig. 14).

Figure 14. Percentage of BEVs in new ZEV sales for each sales year (policy mixes with neutral ZEV mandate, uncertainty range)



Finally, Fig. 15 portrays the effectiveness of policy mixes in GHG emission reductions. Adding policies to the neutral ZEV mandate leads to substantial improvements in 2030 and 2035 GHG emission mitigation. While the addition of a feebate helps to reduce GHG emissions, the addition of a VES has a much bigger impact on GHG emissions. As expected, the policy mixes are more effective at reducing GHG emissions than individual policies.

Figure 15. GHG emission reductions from light-duty vehicles (policy mixes with neutral ZEV mandate, uncertainty range)



Note: The y-axis is truncated at 20MT for the sake of clarity.

5.5 Comparing policy mixes (with BEV-only mandate)

The final set of policy mixes uses the BEV-only mandate as the base. The results are largely consistent with those of the previous section (Figs 16 and 17). The addition of policies to the BEV-only mandate leads to i) increasing ZEV market share, ii) overcompliance in years around 2030, iii) a larger impact on sales from the addition of VES relative to feebate and iv) narrower uncertainty ranges, and thus more certainty, in achieving the 2035 ZEV sales goal.

Figure 16. ZEV market share in new vehicle sales (policy mixes with BEV-only mandate, median case)

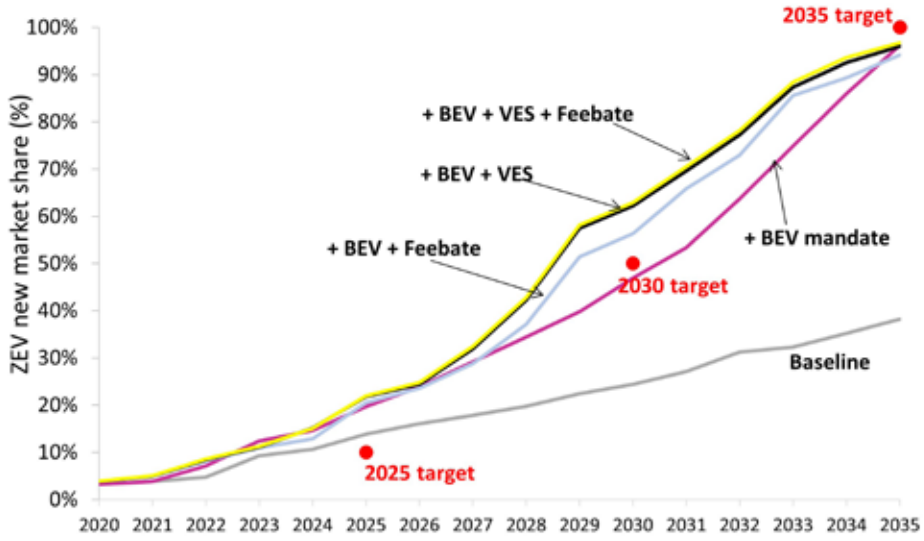
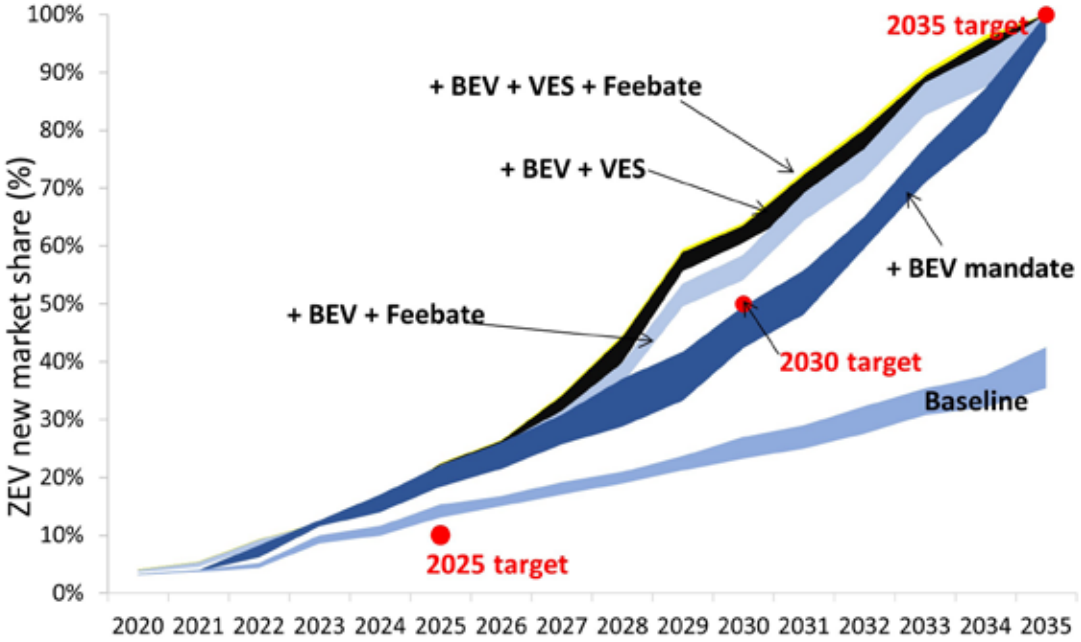
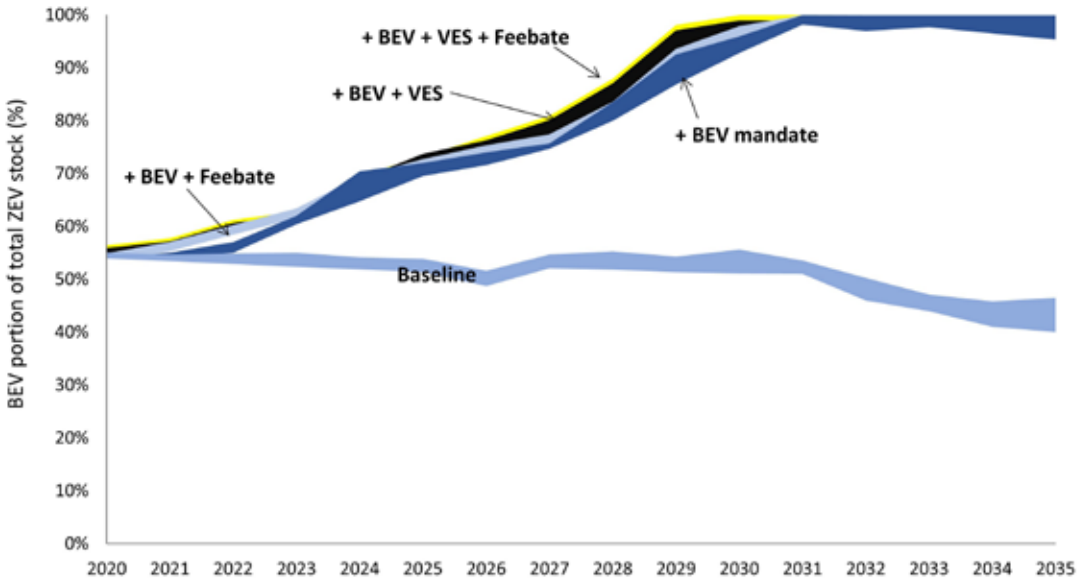


Figure 17. ZEV market share in new vehicle sales (policy mixes with BEV-only mandate, uncertainty range)



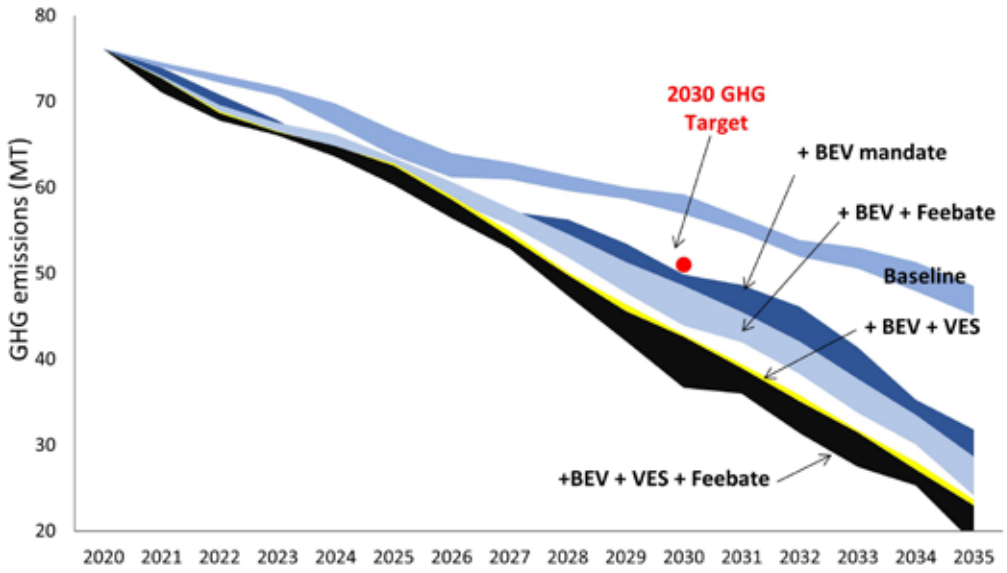
There is little variation in the share of BEVs across these policy mix scenarios, as all include a BEV-only mandate (Fig. 18), though the addition of policies leads to slightly earlier increases in BEV share.

Figure 18. Percentage of BEVs in ZEV sales for each sales year (policy mixes with BEV only mandate, uncertainty range)



As with the neutral ZEV mandate policy mixes, the BEV-only mandate combinations lead to incremental improvements in 2030 and 2035 GHG emission reductions (Fig. 19). The "BEV + VES" and "BEV + VES + feebate" scenarios lead to the most GHG emission reductions out of any other policy scenarios simulated in this study.

Figure 19. GHG emission reductions from light-duty vehicles (policy mixes with BEV-only mandate, uncertainty range)



Note: The y-axis is truncated at 20MT for the sake of clarity.

5.6 Policy costs and scenarios summaries

Table 8 summarizes the key results for each policy scenario. The left half depicts the policy impacts on four indicators:

- The new vehicle market share of ZEVs in 2035;
- GHG emissions in 2035;
- The percentage change (drop) in profits relative to baseline profits (2020-2035); and
- The percentage change (drop) in consumer surplus relative to the baseline (2020-2035).

While the two left-hand columns (ZEV sales and GHG emissions) have been covered in detail above, the focus here is on policy costs and on the trade-offs that come with different levels of GHG mitigation.

Table 8. Policy scenario summary, including policy costs (2035, median scenario)

	ZEV new market share 2035 (%)	GHG emissions 2035 (MT)	Profit impacts 2020-2035 (%)	Consumer surplus impacts 2020-2035 (%)	Total private costs ($/ tonne, 8%)	Total private costs ($/tonne, 3%)	Total gov. expenditure ($ billion, undiscounted)
Baseline	38.3	46.8	0	0	0	0	2.5
Individual policies							
+ ZEV mandate (neutral)	98.7	34.9	-6.8	-3.9	268	478	3.4
+ VES	93.2	31.8	-7.6	-4.8	283	496	4.0
+ Feebate	91.4	36.8	-8.4	-3.3	286	501	0.4
ZEV variations							
+ ZEV mandate (neutral)	98.7	34.9	-6.8	-3.9	268	478	3.4
+ ZEV (PHEV <50)	98.1	32.2	-7.7	-5.1	277	487	3.7
+ BEV mandate (BEV-only)	98.3	31.4	-8.1	-6.3	295	512	4.1
ZEV mandate (neutral) combos							
+ ZEV + Feebate	94.3	30.5	-9.6	-7.2	298	523	4.8
+ ZEV + VES	95.7	24.7	-10.8	-7.7	275	480	4.4
+ ZEV + VES + Feebate	95.8	24.6	-11.1	-7.5	292	507	5.3
BEV-only mandate combos							
+ BEV + Feebate	94.3	27.5	-10.1	-8.1	305	537	5.1
+ BEV + VES	94.7	22.8	-11.0	-8.7	285	499	4.6
+ BEV + VES + Feebate	94.3	21.7	-11.4	-8.3	299	527	3.4

The profit and consumer utility impacts are the two components considered in the total policy cost calculation. Following convention, we frame policy costs as dollars per tonne of GHG emissions mitigated ($/tonne) — the total private cost (consumer surplus and automaker profit) per tonne of CO_2e that is avoided relative to the baseline. Profit losses result from the automaker having to change practices (pricing, R&D investment and other strategies) relative to the baseline, as well as fewer sales and lower profit margins and additional production and scaling costs in the initial years of policy implementation. Consumer utility losses occur because individuals have to move away from their status quo choices, potentially to switch vehicle types, pay more for a vehicle type, and pay more (or less) to drive. As a reminder, costs do not include benefits due to improvements from co-benefits such as air pollution, noise pollution, public health and road safety. Inclusion of these benefits would likely lead to lower costs, and perhaps in some cases net benefits (negative costs).

We see in Table 8 that policies that limit choice (namely a ZEV mandate that puts a cap on PHEVs, or only allows BEVs) will lead to greater losses in both profit and consumer utility. Further, policy combinations that lead to greater GHG reductions also lead to greater losses in profit, consumer utility and government expenditure.

We calculate the total policy costs ($/tonne) of a given policy scenario as the net present value of all profit and utility impacts experienced over the time horizon (2020-2035). We use two different discount rates: i) eight per cent as a more common private discount rate, which puts more emphasis on present and near-term costs and benefits, and ii) three per cent as a more common social rate of return, which puts more emphasis on long-term costs and benefits.

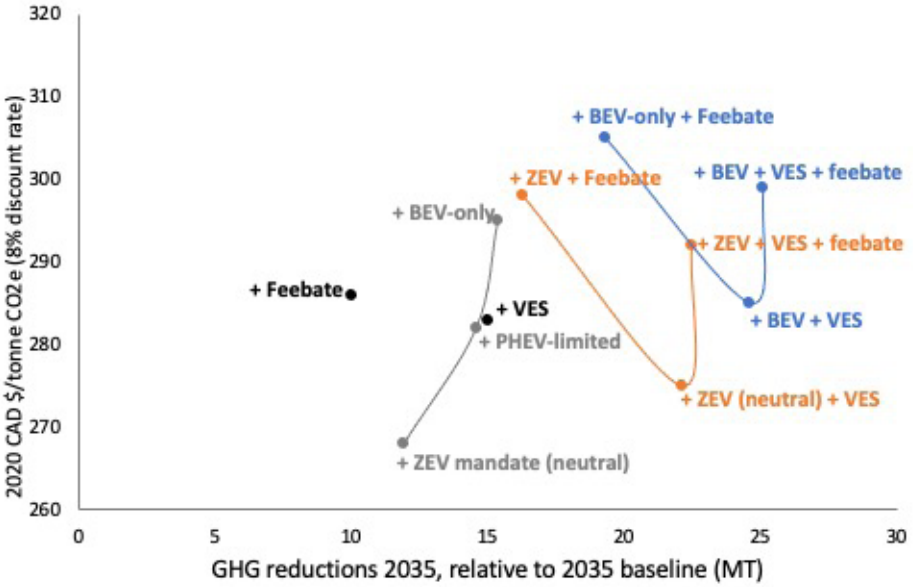
Generally, we see that the most efficient (or more cost-effective) policies are first the neutral ZEV mandate ($268/tonne with eight per cent discount rate), followed by a VES ($283/tonne with eight per cent discount rate). The combination of the two leads to a similarly efficient policy cost ($275/tonne with eight per cent discount rate).

In contrast, the feebate leads to a relatively higher policy cost when enacted individually. Further, policy mixes that contain a feebate tend to be more costly than similar policy mixes that do not. The main reason is that of the policies we explore, a feebate strategy focuses most narrowly on one compliance mechanism: changing the purchase prices of ZEVs and conventional vehicles. In contrast, the VES and ZEV mandate policies incentivize automakers to choose from a variety of compliance options (including cross-price subsidies, as well as R&D investment, increasing vehicle availability and investing in charging infrastructure), and to choose what works out to be the lowest-cost combination of compliance options.

Similarly, policy scenarios that include a PHEV-limited ZEV mandate or BEV-only mandate also tend to be less efficient. In particular, a BEV-only mandate is about 10 per cent costlier than a neutral ZEV mandate. The reasoning is simply that removing more options for consumers and automakers (especially an attractive option like PHEVs, as indicated by various surveys of Canadian car-buyers) will make it costlier to achieve GHG emission reductions targets and ZEV sales goals.

Fig. 20 provides a summary comparison of policy cost-effectiveness by GHG emissions reductions. Aside from scenarios that include a feebate, there is a clear trend: the more effective policies tend to be costlier, which follows the economic principle of increasing marginal mitigation costs. The lowest-cost mitigation strategies tend to occur first (especially in a relatively technology-neutral policy), so a more stringent policy is expected to be costlier in $/tonne — especially in the last units of GHG emissions abated. We see how the three ZEV mandate versions proceed from the least GHG emission reductions and least costly (neutral) to the most effective and most costly (BEV-only).

Figure 20. Comparing policy cost-effectiveness ($/tonne) by 2035 GHG emission reductions (median scenario, 8% discount rate)

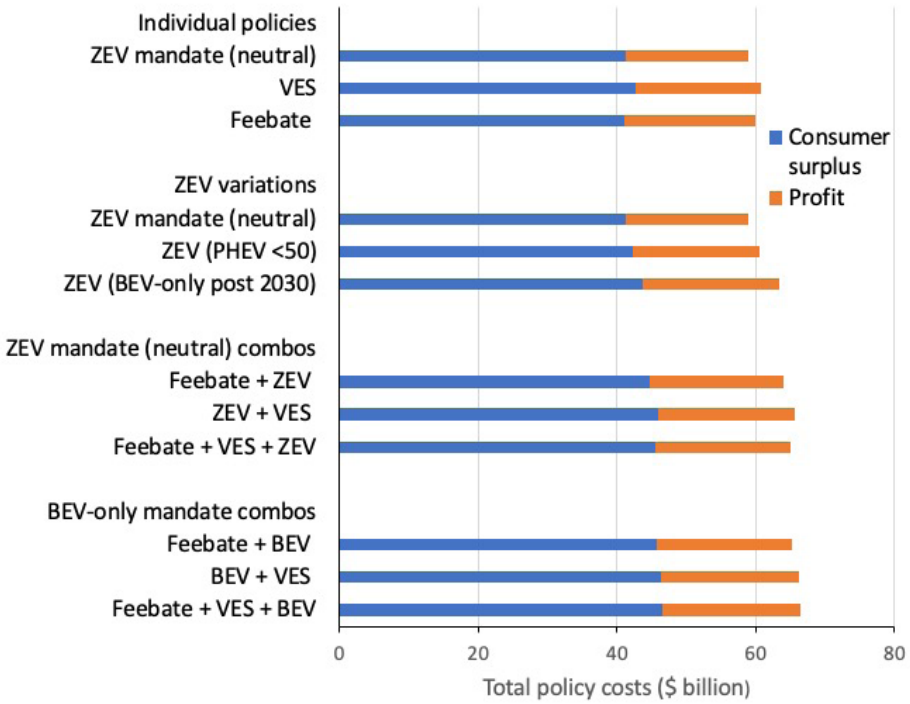


In other words, the increased GHG emission reductions come at an additional cost, because the negative impact on consumer surplus and automaker profitability is higher for the scenarios with higher GHG emission reductions, pushing automakers and consumers further from their baseline decisions. For example, in Table 8, the drops for consumer surplus (-4.8%) and automaker profit (-7.6%) under the Base + VES are higher than those for the Base + ZEV mandate scenario (-3.9 per cent drop in consumer surplus; -6.8 per cent drop in auto industry profits). Further, all of the combinations of two or more policies lead to substantially deeper GHG reductions than an individual policy, but also come at a higher $/tonne cost.

Again, we bring attention to three policy scenarios that provide relatively low-cost options for relatively deep GHG reductions: the neutral ZEV mandate alone, the neutral ZEV mandate with a VES, and a BEV-only mandate with a VES. Among those, the neutral ZEV and VES combination seems to provide a particularly efficient trade-off.

To provide a slightly different perspective, Fig. 21 summarizes the total policy costs (2020-2025, eight per cent discount rate) rather than costs per tonne. Again, more effective policies tend to be costlier, but the ranking is slightly different (as this includes the total cost) and does not consider differences in GHG impact. It is clear that the majority of policy costs (about two thirds across all scenarios) is from loss in consumer surplus, where the rest is from loss in profits.

Figure 21. Total policy costs for each scenario (2020-2035, 8% discount rate)

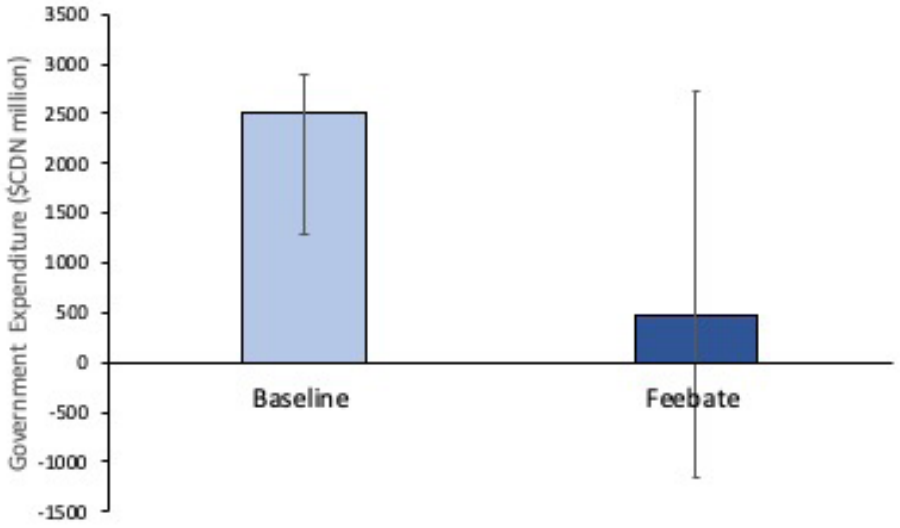


Finally, we consider direct government expenditures, which only accounts for ZEV subsidies that are paid out, minus any fees collected in the case of a feebate. Table 8 provides expenditure numbers for each policy scenario, though Fig. 22 provides the clearest comparison, specifically showing the difference between the baseline and the adoption of a feebate system. We see how the baseline scenario's subsidies lead to about $2.5 billion in total expenditures (in the median scenario), while the feebate leads to less than one-fifth that cost ($400 million). The figure also shows that the feebate is particularly vulnerable to uncertainty. Government expenditures for the feebate program can vary between a cost of over $2.5 billion to a net gain of $1 billion (depending on realized ZEV sales versus conventional vehicle sales). As noted, these extremes could be mitigated if the feebate design (amount of subsidy in fee in each year) was adapted during the modelling time horizon (i.e., changing fees and subsidies each year to achieve revenue neutrality).

We caution against further focus on the government expenditure numbers in other scenarios (in Table 8), as they simply indicate higher expenditures for more ZEV sales while subsidies or a feebate program are in place.

As noted, we use the same feebate scheme (from Section 4.2) in every scenario, which was only designed to be relatively revenue-neutral for the feebate-alone scenario. It would be more realistic — and more advisable — to have an approach that regularly (i.e., annually) adjusts feebate numbers as needed to maintain revenue neutrality.

Figure 22. Total government expenditures in baseline and feebate scenarios (undiscounted)



6. Summary of key findings

This study provides insights into the effectiveness (in terms of ZEV sales and GHG emissions reductions) and cost-effectiveness of several policies for light-duty vehicles. Although a complete policy analysis would need to consider a broader range of impacts (including political acceptability and equity or fairness impacts, as well as co-benefits such as improvements to air pollution, noise pollution, public health and safety), we believe that the present study provides a number of useful insights, which we list here.

1. **The current ("baseline") policies in Canada (as of September 2021) are not nearly strong enough to meet ZEV sales goals (2030 or 2035) or GHG emissions reductions goals (2030).** Even in the "optimistic" conditions regarding ZEVs (assuming low battery prices, high gasoline prices, positive consumer preferences and full deployment of charging infrastructure, among other factors), these policies fall far short.

2. **ZEV sales goals for 2030 and 2035 can be met (or almost met, within a few percentage points) by all three "strong" policies** we have examined here: a ZEV mandate, vehicle emissions standard (VES) or a feebate. In each case, the policy needs to be strong enough (with stringent non-compliance penalties for the ZEV mandate and VES) in order to meet the goal. For example, adding to the existing set of climate policies a ZEV mandate requiring 100 per cent ZEV sales by 2035, or a VES requiring new cars to be 40g/km or lower by 2035. Meeting the 100 per cent by 2035 ZEV sales goal in particular has the potential to be challenging, given that a substantial percentage of consumers in the light-duty vehicle market may still have negative perceptions of ZEVs even in 2035.

3. **Of the three individual policy types, the neutral ZEV mandate is the most cost-effective way to meet the 2035 ZEV sales goal.** The main reason is that it is directly focused on the ZEV sales goal, while providing automakers with a range of strategies to comply (R&D investment, cross-price subsidies, increased vehicle variety and increased charging availability). The ZEV mandate also provides a more certain pathway to achieve the 2035 sales goal (with a narrower uncertainty range compared to the other policies).

4. **Among the three ZEV mandates, there is a trade-off between efficiency ($/tonne), and the depth of GHG reductions**. A ZEV mandate that limits PHEVs at 50 per cent starting 2030 or eliminates them (requiring only BEVs starting 2030) leads to deeper GHG reductions but is less efficient. More specifically, the neutral ZEV

mandate leads to a 25 per cent GHG reduction at $268/tonne; the PHEV limited mandate leads to 31 per cent GHG reductions at $277/tonne; and the BEV-only mandate leads to 33 per cent GHG reductions at $295/tonne. The main reason is that while BEVs lead to more climate benefits than PHEVs, limiting consumer choice will further reduce consumer utility and automaker profits.

5. **Of the three individual policy types, the strong VES provides the deepest GHG reductions by 2035 (second only to the BEV-only mandate)**. Although it comes at a slightly higher cost ($/tonne), the VES provides 2035 emissions reductions (32 per cent relative to baseline in 2035) that are more substantial than the neutral ZEV mandate (25%) and the feebate (21%).

6. **The feebate generally is costlier than the other policies ($/tonne) in terms of private costs (to car buyers and automakers).** It is the costliest individual policy, and any policy mix with a feebate tends to be costlier than a mix without it (without significant increase in GHG reductions).

7. **Of all the policy scenarios we modelled, we think particular attention should be paid to the combination of a neutral ZEV mandate and VES**. This scenario offers relatively deep GHG reductions in 2035 (47 per cent below the baseline in that year), at a cost-effectiveness level ($/tonne) that is second only to the neutral ZEV mandate alone (as noted, the latter only reduces 2035 emissions by 25 per cent).

8. **Combining these three policies (ZEV mandate, VES and feebate) into policy mixes leads to even greater GHG reductions.** All policy mixes lead to emissions reductions that exceed all of the individual policies, ranging from a 35 per cent in 2035 relative to baseline (with a neutral ZEV mandate + feebate), to a 54 per cent reduction from a three-way combination of BEV-only mandate, VES and feebate. However, the efficiency of policy mixes only seems to be favourable in the absence of a feebate (neutral ZEV + VES, or BEV-only mandate + VES). Generally, the incremental improvement in GHG reductions on adding the feebate (to an existing policy mix with strong regulations) is smaller relative to the increase in policy costs, resulting in a decrease in cost-effectiveness. That said, a more adaptive feebate design (that adjusts fees and subsidies in each year to maintain overall revenue neutrality) may be more cost-effective.

9. **Policy scenarios tend to be less efficient (higher $/tonne) when technology options are limited (particularly PHEVs), compliance options are limited (notably a feebate) or overall GHG emissions reductions are greater.** As noted, some of the policies that push for more BEVs (VES and BEV-only mandate) lead to more GHG reductions, but also end up having higher cost (in terms of impacts to consumer surplus and automaker profits).

7. Policy implications

The selection of an ideal policy or policy mix requires consideration of several trade-offs. Here are insights regarding a subset of policy evaluation criteria, namely impacts on:

- ZEV sales;
- GHG reductions;
- Policy costs; and
- The uncertainty of future estimates.

Relative to a feebate, we find a ZEV mandate or VES to be more effective to reduce GHG emissions and more cost-effective. The combination of a ZEV mandate and VES is particularly promising. Using a BEV-only ZEV mandate design can produce further GHG mitigation, but at a higher cost.

To inform a more comprehensive policy evaluation, future research should also consider the political acceptability of each policy, as well as potential equity impacts, which were not studied here. We also acknowledge that our cost-effectiveness calculations do not include societal co-benefits, such as potential improvements regarding air pollution, noise pollution, public health and road safety. Inclusions of these co-benefits would likely lower the costs of each policy scenario we explore here, though we expect the relative ranking of policy scenarios to remain the same.

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9. Appendix: Validation process

1 The structure of the model should follow the general structure of existing simulation models of the automotive market, where such models are available and appropriate.

How AUM performs on validity tests[50]

The basic structure of the model builds on existing literature, wherever one exists.

Consumer model builds on a standard utility function, discrete choice model commonly used in literature to represent consumers (Brand et al., 2017; Axsen and Wolinetz, 2018; Xie and Lin, 2017; National Research Council, 2013). AUM is based on the National Research Council (2012)'s LAVE-Trans model. However, AUM differs in that it does not contain 'Risk perception', 'Charging time' parameters in the utility function. The effect of these parameters is included, however, in the ASC parameter.

Similarly, the automaker model builds upon existing literature such as Michalek et al. (2004), Zhang et al. (2011), and Kang et al. (2018).

Though AUM builds on Michalek et al. (2004) and Kang et al. (2018), it is different and novel on certain accounts; namely longer (multi-period) foresight for automakers, endogenous model variety functionality, endogenous compliance with policies and including the effect of R&D. The other uniqueness of AUM is that it combines a behaviourally realistic consumer model with a detailed automaker model, rarely attempted so far.

Changes when extending the model to 2035

The structure of the model remains the same.

Consumer's utility is depicted using the same nested discrete choice model as in the original 2030 version.

The automaker now has a 15-year foresight, instead of the 10-year foresight as in the previous version up to 2030. As before, the length of the foresight can be changed as needed.

As before the automaker optimizes profits based on four decisions: i) cross-price mark-ups; ii) R&D investment; iii) model variety; and iv) charging infrastructure deployment.

50 Thies, C., Kieckhäfer, K. & Spengler, T. S. Market introduction strategies for alternative powertrains in long-range passenger cars under competition. *Transportation Research Part D: Transport and Environment* 45, 15, doi: https://doi.org/10.1016/j.trd.2015.05.002 (2016).

2 The mechanisms used within the model (e.g., learning by doing, experience spill over, purchase decisions) should be based on well-founded theories.

How AUM performs on validity tests

Learning effects built upon Barreto and Kypreos (2004). Similarly, consumer purchase and profit maximization decisions are based on economic theory (Goldberg, 1998; Austin and Dinan, 2005; Bento et al., 2009; Jacobsen, 2013; Small, 2017)

Changes when extending the model to 2035

As before, we base our model on economic theory and literature. No changes were made on this account.

3 The equations connecting the model variables should be dimensionally consistent.

How AUM performs on validity tests

This requirement implies that the order and shape of the mathematical functions are appropriate for the specific functionality. For example, as opposed to a linear function, a logit function (Equation 1) is more suitable for estimating market share, since the maximum (1) and the minimum (0) values of a logit correspond to the theoretical maximum (100%) and minimum (0%) values that ZEV market share can attain.

Similarly, a quadratic function (equation 5) more closely represents a typical cost curve as opposed to a linear or cubic function.

Changes when extending the model to 2035

As before, equations have been checked for dimensional consistency.

4 The model boundary and the aggregation level should be appropriate to address the specific research questions.

How AUM performs on validity tests	Changes when extending the model to 2035
The research questions intended to be answered using this model include: (1) examining the impacts of the design features of supply focused policies (e.g. ZEV mandate) on outcome indicators such as new vehicle market share and automaker profitability; (2) examining different types of interactions between supply focused policies; and (3) examining different compliance mechanisms for automakers. The model appears well-equipped to handle these questions. The model is narrow in scope (it only focuses on light-duty vehicles), but it is relatively detailed in representing endogenous automaker strategies, supply-side policies as well as behaviourally realistic consumers. Having multiple automakers would have improved the model further. However, the level of disaggregation and computational complexity appears similar to other PEV market share forecast models such as REPAC (in Axsen and Wolinetz, 2018) and CIMS (Jaccard et al, 2003), and seems appropriate for the current work.	No changes required here.

5 The model parameters should be based on empirical data, as far as possible.

How AUM performs on validity tests

The majority of parameters in the AUM model borrow from empirical data collected via Canadian surveys (Axsen et al., 2015; Kormos et al., 2019) and we use data from other models (e.g., National Research Council, 2013) where empirical data is not available.

Changes when extending the model to 2035

Input values have been updated as follows:

1. Fuel prices for 2035 from the International Energy Agency (IEA) (2021)

2. Model variety reaches 100% by 2035 in the median case, in line with automaker announcements (Ford, 2021; GM, 2021).

3. Charger availability reaches 100% by 2035 in the median case, in line with government announcements (Government of Canada, 2021)

4. Range: High-range EVs existed in the 2030 version as well. They remain unchanged.

5. Fuel costs: Fuel costs for ZEVs decrease in line with decreasing electricity prices (National Energy Board, 2020), reach $0.019/km by 2035.

6. Consumer preferences (i.e., ASC) were updated (Table 2) to reflect faster than previously anticipated improvement in consumer preferences over time. Rationale for updating consumer preferences- 1) Feedback from reviewers on previously submitted articles who pointed out that consumer preferences may improve faster than we were assuming in the original version. 2) For the original level of consumer preferences, the new vehicle sales in 2035 were dropping by greater than 30% relative to the Baseline sales in 2035, under the effect of the ZEV mandate (with 100% ZEV requirement by 2035).

As a simplifying assumption, we assume that consumers' marginal utility of income (as captured by the purchase price coefficient) stays the same from 2020 to 2030 (original version) and to 2035 (extended version). The coefficients for other parameters are held constant at 2020 levels, as in the 2030 version.

Other supply side parameters (e.g., learning rates, automaker discount rates) were left unchanged.

6 Ensure that the model produces plausible, realistic output behaviour.

How AUM performs on validity tests

We generate a series of model sub-outputs (e.g., market share, vehicle costs, vehicle prices) for the Baseline scenario to ensure that these values are realistic, comparing the results to other modelling studies or real-world data. As one example, the new light-duty vehicle market share estimated by the model for Canada matches real-world data for the years 2018, 2019 and 2020 (Fig. 4). Sections 4.1-4.2 in the main article present Baseline scenario projections endogenously generated by the model.

Estimates in grey literature suggest that gross profit margins per vehicle vary between $4,000 and $13,000 (Motor Monitor, 2020). Averaging over the two million vehicles sold in 2019 in Canada, this gives a value of about $14-15 billion as gross profit for the auto industry. This value is similar to the value estimated by the model. Similarly, Canadian Vehicle Manufacturing Association informs that the auto manufacturing industry contributes about C$20 billion to the Canadian economy (CVMA, 2020).

Changes when extending the model to 2035

Behavioural tests conducted:

1. Under the Baseline scenario (with current policies; e.g., tax, fuel standard, current VES), the new market is expected to be between 35-42%, in line with estimates by Transport Canada (Transport Canada, 2021).

2. Endogenously estimated vehicle costs. under the Baseline scenario for the sedan class, under the median case are as follows: BEV-380 ($20,125 in 2025; $18,775 in 2030; $16,543 in 2035); PHEV -60 ($20,085 in 2025; $19,200 in 2030; $19,300 in 2035). The vehicle production costs and corresponding prices are similar to Lutsey et al.'s (2021) bottom-up estimates for PEV prices.

3. New vehicle sales were 1.5 million light-duty vehicles in 2020, dropping 20% from 1.9 million in 2019 (1.8 million in 2018). In a recent report, the government of Canada assumes 1.72 million new sales in 2023, 1.75 million in 2024, and 1.8 million in 2025 (Environment and Climate Change Canada, 2021). IEA (2021, 131) estimates global new vehicle sales to grow at about 1.7% annually. The endogenously estimated new vehicle sales under the Baseline scenario are 1.6 million in 2035, which is in line with literature as discussed above.

4. The auto industry contributed $20 billion to the Canadian economy in 2019. Assuming a growth similar to Canadian GDP growth rate (~2%), the auto industry contribution may be around $26 billion by 2035. Our model estimates gross profits to be $20 billion in the Baseline median case.