Light-Duty Vehicle Policy Mixes for Climate Goals: Modeling Effectiveness, Efficiency and Automaker Response

By

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Abstract

The reality of political acceptability has led policy makers to implement policy mixes which often include supply-focused regulations, such as a zero-emissions vehicle (ZEV) mandate or vehicle emissions standard (VES). I look more closely at policy mixes that include regulations, to explore how policies might be designed to effectively and efficiently achieve climate targets within the light-duty vehicle sector (using the case of Canada). In this effort, the thesis includes four research papers.

In the first research paper I review the broader, mostly non-transport literature and identify several rationales for pursuing policy mixes. Based on this review, I develop a framework to guide the examination of policy interactions across multiple criteria, namely GHG mitigation, cost-effectiveness, political acceptability, and transformative signal. I demonstrate this framework by setting hypotheses for interactions across six light-duty vehicle policies. In the second paper I develop and apply the AUtomaker-consumer Model (AUM) to examine automaker response to a ZEV mandate. AUM endogenously represents multi-year foresight for the automaker, including decisions about: (i) increasing ZEV model variety, (ii) intra-firm cross-price subsidies, and (iii) investing in R&D to reduce future ZEV costs. I simulate the case of a ZEV mandate (requiring 30% ZEV sales by 2030) and find that of the three compliance mechanisms, intra-firm cross-price subsidization dominates. In the third research paper, I use AUM to examine the impacts of different policy designs (with varying non-compliance penalties and credit schemes) on ZEV adoption, consumer surplus and industry profits. I find that a higher penalty for non-compliance (CAD$ 10k per credit) is needed to achieve the 30% by 2030 policy target. Compliance is further impacted by the allocation of ZEV credits. In the fourth paper, I compare several policies in terms of effectiveness (reaching 2030 GHG mitigation goals) and mitigation costs, namely: (i) a carbon tax; (ii) a VES; (iii) a ZEV mandate, and (iv) combinations of all three at alternative stringencies. Among regulations, the VES is cheaper than a ZEV mandate at lower stringencies, but at higher stringencies the two are similarly efficient (both incentivize widespread ZEV deployment). In policy mixes, cost-effectiveness is improved by a carbon tax.

Keywords: Climate policy; Technology adoption model; Policy mixes; Automaker behaviour

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Table of contents

Declaration of Committee	ii
Abstract	iii
Acknowledgements	v
Table of contents	vi
List of figures	ix
List of tables	xi
Chapter 1 Introduction	1
1.1 Climate policies for light-duty vehicles	1
1.2 Challenges in policy evaluation	3
1.3 Challenges in transport modelling	5
1.4 Summary of dissertation papers	6
Chapter 2 Why have multiple climate policies for light-duty vehicles? Policy mix rationales, interactions and research gaps	13
2.1 Introduction	14
2.2. Gaps in transport policy mix literature	17
2.3. Different perspectives and rationales regarding policy mixes	18
2.3.1 The “three-legs” perspective	19
2.3.2 The “multiple market failures” perspective	20
2.3.3 The “political process” perspective	23
2.3.4 The innovation systems perspective	25
2.3.5 Insights and implications for light-duty vehicle climate policy	29
2.4. Proposing a framework for policy mix interactions	30
2.5. Illustration of potential policy interactions: Hypotheses for the case of British Columbia, Canada	34
2.6. Discussion and conclusions	45
Chapter 3. Simulating automakers’ response to zero emissions vehicle regulation	52
3.1. Introduction	53
3.2. Literature review: ZEV adoption models	54
3.3. Method	58

3.3.1 Demand-side: The consumer choice model 60
3.3.2 Supply-side: The automaker model 67
3.3.3 Policy scenarios 73
3.4. Results 74
3.4.1 Baseline estimates of vehicle manufacturing costs and prices 74
3.4.2 PEV new market share results 75
3.4.3. PEV adoption impacts 77
3.4.4 Automaker pricing strategies 79
3.4.5 Automaker supply strategies (R&D and model variety) 81
3.4.6 Impacts to automaker profits 83
3.5. Discussion and Conclusion 86
Chapter 4. How does a zero-emissions vehicle (ZEV) mandate impact automakers and consumers? Simulating Canada's light-duty vehicle sector using the AUM model 91
4.1 Introduction 92
4.2 Model 94
4.3. Results 96
4.3.1 The impacts of ZEV penalty 96
4.3.2 The impacts of ZEV credit scheme 100
4.3.3. The impacts of ZEV credit banking 103
4.3.4. Sensitivity analysis 104
4.4. Conclusion and Policy Implications 106
Chapter 5. Which "second-best" climate policies are best? Simulating cost-effective policy mixes for passenger vehicles 108
5.1 Introduction 110
5.1.1 Literature on climate policy cost-effectiveness 112
5.1.2 Current study 115
5.2 Model 117
5.2.3 Calculating policy costs 117
5.2.4 Policy scenarios 120
5.3. Results 122
5.3.1 Current baseline and individual policies 122
5.3.2 Policy combinations 126

5.4. Discussion and conclusions 131

Chapter 6. Discussion & Conclusions 136
6.1 A framework for policy mixes and interactions 137
6.2 Developing AUM to model supply-focused climate policy for light-duty vehicles 139
6.3 Using AUM to simulate the impacts of ZEV mandate design 141
6.4 Using AUM to evaluate the cost-effectiveness of supply-focused regulations and policy mixes 144
6.5 Conclusions and Policy implications 146
6.6 Limitations and Future Research Directions 148

References 151

Supplementary Information 166

List of figures

Fig. 1.1 ZEV new market share under policy scenarios 9

Fig. 1.2 Automaker profits (total) under the Baseline and ZEV mandate policy scenarios. 10

Fig. 1.3 ZEVs new vehicle market share in Canada under the Baseline and ZEV penalty scenarios 11

Fig.1.4 Change in the cost effectiveness of individual policies with increasing policy stringency, plotted against the corresponding GHG reductions 12

Fig. 3.1 Structure of the AUtomaker-consumer model (AUM) 59

Fig. 3.2 Nested structure of the vehicle choice model. 61

Fig. 3.3 Endogenously estimated vehicle manufacturing costs and retail vehicle prices under the Baseline scenario 75

Fig. 3.4 PEV new market share under policy scenarios 76

Fig. 3.5 Sensitivity analysis of PEV new market share in the Baseline and ZEV mandate scenarios in 2030. 77

Fig. 3.6. PEV new vehicle market share by consumer segment- Enthusiasts (15%), Mainstream (50%) and Resistors (35%), under the Baseline and ZEV mandate scenario 78

Fig. 3.7 Difference in the composition of the total PEV sales under the ZEV mandate and the Baseline scenario 79

Fig. 3.8 Markups for CVs, BEVs and PHEVs under the (i) Baseline and (ii) ZEV mandate scenario. 80

Fig. 3.9 Average R&D investment per vehicle under the ZEV mandate and the Baseline scenarios 81

Fig. 3.10 Total number of models (or model variety) supplied by the automaker under the ZEV mandate and the Baseline scenarios 83

Fig. 3.11. Automaker profits (total) under the Baseline and ZEV mandate policy scenarios. 84

Fig. 3.12 Sensitivity analysis of the change in automaker profits under the ZEV mandate (relative to Baseline) in 2030 85

Fig.3.13 Breakdown of total profit drop for the median case into constituent components, 86

Fig.4.3. ZEVs new vehicle market share in Canada under the Baseline and ZEV penalty scenarios 97

Fig. 4.4 Percentage change in consumer surplus under the ZEV penalty scenarios relative to the Baseline 98

Fig. 4.5 Percentage and total change in automaker industry profits under the ZEV penalty scenarios relative to the Baseline 99

Fig. 4.6 ZEVs new vehicle market share in Canada under the Baseline, ZEV Equal Credit scenario (with and without Banking) and California style scenario (with and without Banking) 100

Fig. 4.7 PHEV sales as a percentage of the total ZEV new market share under the ZEV Equal Credit scenario (with and without Banking) and California style scenario (with and without Banking) 101

Fig. 4.8 Percentage and total change in automaker industry profits relative to the Baseline under the ZEV Equal credit scenario (with and without Banking) and California style scenario (with and without Banking) 102

Fig. 4.9 Percentage change in consumer surplus relative to the Baseline under the ZEV Equal Credit scenario (with and without Banking) and California style scenario (with and without Banking) 103

Fig. 4.10 Sensitivity analysis of PEV new market share in the ZEV mandate scenario in 2030 105

Fig. 4.11 Sensitivity analysis of the change in consumer surplus under the ZEV mandate in 2030 105

Fig. 4.12 Sensitivity analysis of the change in automaker profits under the ZEV mandate in 2030 106

Fig. 5.2. WTW GHG emissions (in million tonnes) to 2030, under different policy scenarios 123

Fig.5.3 Change in the cost effectiveness of individual policies with increasing policy stringency, plotted against the corresponding GHG reductions 125

Fig.5.4. Cost effectiveness of alternative policy mixes with increasing policy stringency, plotted against the corresponding GHG reductions 129

List of tables

Table 1.1 Framework for evaluation of policy interactions 8

Table 2.1 The “three legs of the stool” perspective 19

Table 2.2 Examples of multiple market failures 22

Table 2.3 List of failures across the system that justify policy mixes 27

Table 2.4 Framework for evaluation of policy interactions 32

Table 2.5: Hypotheses for potential policy interactions 37

Table 3.1: List of representative ZEV market share modelling studies 56

Table 3.2: List of attributes and the corresponding estimated Willingness to pay values of their coefficients 65

Table 3.3: Optimistic, Reference and Pessimistic values for key model parameters 66

Table 3.4: Exogenous parameters used in the automaker model 69

Table 5.1 Vehicle energy intensity and fuel carbon intensity (Canadian) assumptions 119

Table 5.2 Effectiveness of policy combinations 127

Chapter 1. Introduction

1.1 Climate policies for light-duty vehicles

The combustion of fossil fuels in the transport sector contributes about one quarter of the annual greenhouse gases (GHG) emitted globally, with about 72% thereof coming from road transport (Sims et al, 2014; IPCC, 2014). The light-duty vehicle sector in particular constitutes about two-thirds of the road-based emissions globally (IEA, 2021). This trend is seen more locally as well, where light duty vehicles account for 11% of Canada's total GHG emissions (Government of Canada, 2021). In light of this, governments across the world are devising policy strategies to reduce GHG emissions from road transportation, and in particular the light duty vehicle sector. For example, the Canadian government has committed to reducing GHG emissions by 40% (relative to 2005 levels) by 2030, and of reaching near zero emissions by 2050 (Government of Canada, 2021).

There is general agreement that a technological shift away from conventional fossil-fuel based technologies and towards zero emission vehicles (ZEVs) needs to occur to achieve deep GHG reductions (McCollum and Yang, 2009; Stiglitz et al, 2017; Sperling, 2018; IEA 2021). ZEVs include plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), as well as hydrogen fuel cell vehicles (HFCVs). While PHEVs can run on both electricity and gasoline, BEVs run purely on electricity, and HFCVs[1] are powered by hydrogen. In addition to being two- to four-times more efficient than conventional internal combustion engine (ICE) models, ZEVs can reduce reliance on oil-based fuels and, if running on low-carbon electricity, can deliver significant reductions in GHG emissions (IEA, 2021).

For this reason, multiple regions have implemented ZEV-specific policies. As one example, the ZEV mandate was first implemented by California in 1990 (and 10 other US states), and versions have more recently been implemented in China and Canada (Quebec and British Columbia). A ZEV mandate requires automakers to produce (for sale) a certain percentage of their total vehicle fleet annually to be ZEVs (CARB, 2017). Each ZEV produced earns some credits which counts towards the ZEV requirement. For example, California had a ZEV credit requirement of 4% in 2020 rising up to 22% by 2025 (with a

[1] Though, my current analysis does not include HFCVs, on account of the fact that HFCVs are likely to be a small share (~1%) of the light-duty ZEVs up to 2030 (IEA, 2021).

longer-term target of 100 % ZEV market share by 2035) (Government of California, 2021). British Columbia, Canada, more recently introduced a ZEV mandate that follows California's requirements until 2025, but then requires 30% ZEV new market share in 2030, and 100% by 2040. The ZEV mandate, however, remains understudied in literature, where there is lack of clarity on its effectiveness (in increasing ZEV sales and reducing GHG emissions) and how automakers may comply (if at all) with the policy. There is also little research on how its design features may affect GHG mitigation, in addition to its welfare impacts, and its interactions with other policies.

While in many countries there is consensus on the need for deep GHG reductions (e.g., the Canadian government's target of near zero GHG emissions by 2050), opinions vary on the policy approaches which should be adopted to achieve GHG reductions in the light-duty vehicle sector. Some economists have typically recommended the use of a singular policy (namely the carbon tax) (Nordhaus, 2011). Though, real world policies look different, where policymakers have preferred the use of policy mixes (i.e., multiple policies implemented simultaneously).

Approaches may also vary in terms of their focus on the demand or supply-focussed policies. As one example, the US State of California has adopted a number of novel supply-focussed regulations as part of their broad mix of climate policies. Supply-focussed policies are those that directly force or incentivise vehicle or fuel suppliers to produce new technology and supply alternative fuels (Greene and Ji, 2016). Examples implemented in California include the ZEV mandate and the low carbon fuel standards (LCFS). The LCFS mandates the fuel suppliers to reduce the carbon intensity (in gCO_2e/MJ) of the fuel supplied, either by fuel mixing (e.g., mixing low-carbon ethanol with gasoline) or reducing life cycle carbon intensity (e.g., carbon capture storage) of the fuel. In contrast, demand focussed policies are policies that seek to directly affect consumer demand for a particular technology, for example ZEV purchase subsidies or taxes (Creutzig et al, 2018). There is scope for research on whether supply or demand focussed policies or a combination of these is most suitable for reducing GHG emissions at low costs and in a political-friendly way.

Selecting and implementing the most suitable transport climate policy has proven to be complicated (Nordhaus, 2019), at least partly due to two broad categories of challenges: i) challenges in academic understanding of policy evaluation, and ii) challenges in the models used to analyse policies. The two are related since modeling challenges also lead to blind-spots for policy evaluation. For example, and as I explain further down, some models focus only (or mostly) on consumer decisions, and others focus on automaker decisions – but representing only one side of the economy can provide misleading results about policy effectiveness and efficiency. I discuss each category of challenge in turn in sections 1.2 and 1.3 respectively.

1.2 The challenges of policy evaluation

As noted above, policy mixes (having multiple policies that address a similar issue) are often implemented across various jurisdictions. These policy mixes vary in the number of constituent policies, in the types of policies included, as well as in the stringencies (or other design features) of each constituent policy. However, multiple policy evaluation challenges (e.g., policy mixes, policy interactions, policy stringency) have received little attention in literature so far. I outline three important challenges.

First, as I outline further in my first research paper (Bhardwaj et al., 2020), policies often need to perform well on multiple criteria. To meet the GHG mitigation goal, a climate policy needs to be effective in reducing emissions. We may also want the policy to be economically efficient (or cost-effective), such that it could achieve the goal at a relatively low cost to social welfare (say, per tonne of CO_2e mitigated), including sub-components such as consumer utility, and industry profits. Unless stated otherwise, all costs in this thesis are in Canadian dollars. But if the policy is likely to trigger strong opposition (i.e., it is political unacceptable), that may affect the likelihood of the policy being implemented in the first place (Rhodes et al, 2017). In addition, a climate policy should induce technological change (Stern, 2006; Kalkuhl et al, 2012), where it may be expected to trigger a long-term societal and technical push towards low-carbon systems (technology and practices) (Rogge and Reichardt, 2016). Transport climate policy literature has paid less attention to the simultaneous consideration of multiple criteria. The focus has largely been on effectiveness and cost-effectiveness (Marsdon and Reardon, 2018), potentially because it is easier to quantify policy impacts on these criteria but difficult to quantify for political acceptability and technological change.

A second challenge is the evaluation of policy mixes, which necessitates evaluation of policy interactions. For example, British Columbia in Canada is impacted by a number of different policies, such as a vehicle emissions standard, low-carbon fuel standard, and zero-emissions vehicle standard, as well as ZEV purchase subsidies, non-financial incentives (such as high-occupancy vehicle lane access) and charging infrastructure deployment. The presence of so many policies makes it difficult to empirically analyze (or anticipate) whether some or all policies are beneficial and needed. There may exist interactions between policies affecting the performance of the policy mix (May et al, 2006; Howlett and Rayner, 2007; Rogge and Reichardt, 2016). Two or more policies can be “complementary” on a given criterion if their combined performance is improved due to a positive interaction, or they could interfere and lead to a decrease in the combined performance. As one example California has implemented the ZEV mandate with the goal of increasing ZEV sales, whereas simultaneously a vehicle emission standard (VES) is also in place in the U.S. nationally. The two policies could potentially interact negatively (or interfere) with each other and lead to an overall increase in GHG emissions instead of the intended reduction (Jenn et al, 2019). In another example, a carbon tax and a VES could interact positively or be complementary in reducing policy costs, where a combination of the two policies could be more cost-effective than the VES alone (Small, 2012). Transport climate policy literature has largely focussed on analysing policies in isolation, and has paid little attention to examining policy mixes and the interactions between these policies (Lam and Mercure, 2021).

A third challenge is that of policy design stringency, where transport climate policy literature often compares policy categories more broadly, e.g., tax versus regulation, while effectiveness and efficiency can both vary depending on policy stringency (Pahle et al, 2018). On the one hand, more stringent policies seem likely to experience higher overall costs, as the lower-cost responses or compliance options become exhausted – leading to an increasing mitigation cost curve (Carley et al, 2018; Pahle et al, 2018). On the other hand, some forces of technological change suggest that a stronger or more focused regulation might induce learning curves and technological change more quickly, which in some cases can decrease policy costs in the long-run (Fox et al. 2017). It is thus important for policy analysis to consider a broad range of policy stringencies, individually and in combinations within a policy mix.

A related challenge is consideration of other aspects of policy design, aside from policy category and stringency. As one example, the Californian ZEV mandate has several design features. Under California-style ZEV mandates, different vehicle types earn different number of credits. To illustrate, BEVs on average earn higher (between 1 and 4) credits than PHEVs (between 0.5 and 1.2), because BEVs have a longer electric range. Another design feature is the penalty for non-compliance, where current North American versions of the ZEV mandate (e.g. in California, Quebec and British Columbia), impose a penalty of US$ 5000 per credit for non-complying automakers. For the ZEV mandate, and for other policies more generally, little is known about how such design features will affect policy outcome.

In summary, a number of challenges remain in the way transport literature has examined climate policies thus far: focus has largely been on one (or two) criteria, lacking a multicriteria evaluation of policies; little research has examined policy mixes, as well as the resulting interactions between policies; and the effect of policy stringency and design, in particular for supply-side regulations, has largely remained unexplored. I attempt to bridge some of these gaps in my thesis. Next, I address some of the challenges of transport modeling that relate to these difficulties and gaps in transport policy evaluation.

1.3. The challenges of transport modeling

Quantitative models can be particularly helpful in anticipating the various impacts of climate policy (Sovacool et al, 2018). Given the importance of the role of new and emerging ZEV vehicle technologies in GHG mitigation (Sperling, 2018; Stiglitz et al, 2017; IEA, 2021), technology adoption models, which focus on how a specific technology gets adopted over time, have become popular for transport climate policy analysis. Such models have been used to simulate new vehicle market share (e.g., Axsen and Wolinetz, 2018), as well as estimate GHG impacts and policy costs (Lam and Mercure, 2021; Fox et al, 2017). Arguably, models used to examine climate policies in the real world should be able to represent the behaviour of various agents (e.g., consumers and automakers) accurately, as well as capture the evolution of technology. For example, to examine interactions between policies (a policy evaluation challenge identified in section 1.2), models should be able to endogenously represent how an agent (e.g., automaker) responds when impacted by two or more policies simultaneously. Also, to be able to examine the development of policy interactions over time, models need to be able to simulate long-run dynamics in behavior and technology. However, some methodological challenges in technology adoption models deserve attention.

The first challenge is behavioural realism (or consumer-side features), which entails that consumer purchase decisions for light duty vehicles, are also influenced by non financial factors, such as technology awareness, or risk (Axsen and Kurani 2013; Heffner et al., 2007). Behavioural realism may also include representation of consumer heterogeneity, which recognizes that different consumers in a market will have different technology preferences (Jaccard, et al, 2009; Higgins et al., 2017). In addition, behavioural realism may require that consumer preference should be dynamic, since preferences for novel, alternative technologies can improve over time as more and more consumers adopt the technology due to the "neighbour-effect" (Axsen et al, 2009). Some models represent consumer heterogeneity in a sophisticated way, for example, using multiple consumer segments (e.g., NRC, 2013; Gnann et al, 2014). Some others represent consumer learning, including dynamic consumer preferences (e.g., Fox et al, 2017; Lam and Mercure, 2021). However, as Xie and Lin (2017) point out, many models used for transport climate policy analysis typically do not represent consumer behaviour in detail, ignoring features such as multiple consumer segments, as well as dynamic consumer preferences (e.g., Michalek et al., 2004; Whitefoot et al., 2017; Jenn et al, 2019).

The second challenge is the explicit representation of supply-side features, including transport actors (e.g., automakers[2]), and the effect of other supply-side dynamics (e.g., lack of variety and availability in ZEV makes and models). Automakers may respond to supply-focused policies (e.g., a ZEV mandate) in a variety of ways: such as offering ZEVs at discounted prices to influence sales mix, or investing in R&D to reduce ZEV production costs (Mazur et al., 2015) among others. Some models represent automaker decision making endogenously and often in great detail with multiple automakers, vehicle technology types, and vehicle classes (e.g., Michalek et al., 2004; Whitefoot et al., 2017; Jenn et al, 2019) – though most of these models do not represent consumer behaviour in depth. However, most models do not explicitly represent the automaker response to policies (e.g., NRC, 2013; Gnann et al, 2014; Fox et al., 2017; Lam and Mercure, 2021), limiting their ability to accurately capture the producer -consumer dynamics, as well as endogenous learning effects at the automakers' end.

A third challenge is technological change, which needs to be modelled in any simulation of long-term adoption impacts of various ZEV technologies (or other emerging, low-carbon technologies). Many models only represent technological change exogenously, with the costs of low-carbon technology decreasing at a fixed rate over time (regardless of uptake patterns or the strength of policy). Endogenously representing technological change

[2] In this study, I focus on automakers, while many of my concerns also could apply to fuel suppliers (and the policies that focus on them).

includes concepts such as learning by doing and learning by searching (Nordhaus, 2014; Popp and Pizer, 2008). For example, learning by doing simulates how production costs of alternative technology (e.g., electric vehicles) change or decrease as a function of increased production. Learning by searching attempts to capture the endogenous decline in production costs as a result of research and development (R&D) activities. Modelling studies like those by Fox et al (2017) and Lam and Mercure (2021) include some components of technological change, such as rich technological details, covering multiple vehicle classes and drivetrains, and represent learning by doing as vehicle costs go down with increasing sales. Technological change, however, can be better simulated through explicit representation of both the supply-side and consumer side and the dynamic interactions between them, which is lacking in most models (e.g., Fox et al, 2017; Lam and Mercure, 2021). Moreover, these and other studies in this space typically lack a representation of learning by searching effects.

In summary, various models have their strengths and weaknesses. The first criticism, pertaining to some the of the models representing transport sector, is the lack of behavioural realism. A second limitation of many technology adoption models is that they represent the supply side (namely, automakers and fuel supplier), and thus supply-focused policies, simplistically or not at all (Greene and Ji, 2016). The third criticism is that technological change is simplistically represented. Technology learning in most models is exogenously assumed, and details about emerging technologies (such as ZEVs) are often not considered. Overall, there exists a lack of modelling studies in literature that simultaneously address all these criticisms. The goal of my research work is to address this gap.

1.4. Summary of dissertation papers

To address the gaps relating to the two broad categories of challenges identified above, I operationalize my work into four goals. This thesis is divided into six chapters, with chapters 1 and 6 as the introduction and conclusion respectively. The remaining chapters (2-5) represent four research papers, corresponding to each of the four research goals.

My first goal (chapter 2) is directed towards the challenge of policy evaluation. I adopt a qualitative approach to examine policy mixes and policy interactions more closely. In this effort my objectives are to: (i) identify gaps in the transport literature regarding policy mixes; (ii) identify rationales for policy mix use; (iii) propose a general framework to guide exploration (and hypothesis generation) regarding interactions between climate policies; and (iv) identify critical research gaps to support the design and evaluation of policy mixes. I review and draw insights from the broader, mostly non-transport literature and identify several rationales for pursuing mixes of policies: the "three legs" approach to transport decarbonization, the "market failure" perspective, the "political process" perspective, and the "systems" perspective. Based on this review, I develop a simple framework for examining policy interactions across multiple criteria, namely GHG mitigation, cost-effectiveness, political acceptability, and transformative signal (Table 1.1). I demonstrate this framework by setting hypotheses for interactions across six light-duty vehicle policies in the case of British Columbia, Canada, as well as identifying research gaps and directions for improvement in quantitative models.

Table 1.1 Framework for evaluation of policy interactions (climate policies for light-duty vehicles)

Policy interaction criterion	Explanation	Quantitative measure	Sub-components
1) Effectiveness at GHG mitigation	Does the policy lead to additional GHG mitigation?	Tonnes CO_2e abated, in a given year, e.g., 2030 or 2050 (ideally well-to-wheel or full Life Cycle Analysis)	Can be evaluated in aggregate, or split by "Three legs": 1. Carbon intensity of fuel (gCO2/MJ) 2. Vehicle efficiency (MJ/km) 3. Vehicle usage (VKT)
2) Cost-effective	Does the policy improve (or worsen) the cost-effectiveness of the policy mix?	$/Tonne CO_2e abated, or consumer utility	Can be evaluated in aggregate (total social welfare), or broken down, e.g., by: 1. Consumer utility 2. Industry profit 3. Government expenditure 4. General equilibrium impacts
3) Political acceptability	Does the policy improve (or worsen) the political acceptability of the policy mix?	Not as clear. Percentage of citizens or stakeholders that support or oppose the policy? Directly ask the perceptions of the policymaker?	Can be split between citizens and special interest groups. May need to focus on interest groups with particular clout in a particular context (e.g., automakers in a region with more auto-related manufacturing).
4) Transformational signal	Aside from the above factors, does the policy provide an added "push" in transition towards the low-carbon goal?	Unclear how to quantify in general. Specific measures could be dollars invested in R&D activity, or number of patents or prototypes per year. Infrastructure can be measured by density (relative to gasoline/diesel equivalent).	Can draw from Weber and Rohrachers's (2012) framework, including: 1) Signal for R&D investment 2) Provision of physical infrastructure 3) Break "lock-in" 4) Pathway directionality

My second goal (chapter 3) aims to address the challenges in transport modelling. I attempt to address this by developing AUM (or AUtomaker-consumer Model), a technology adoption model, that endogenously simulates automaker-consumer decision-making and behaviour to examine the effects of individual policies, policy mixes as well as examine policy interactions. AUM is specifically designed to: (i) represent consumer behaviour (heterogeneity, non-financial factors and dynamic consumer preferences); (ii) represent supply-side policies (using a representation of forward-looking automaker behaviour); and (iii) incorporate endogenous technological change (learning by doing and learning by searching, including feedbacks). To demonstrate AUM, in this study my overall objective is to simulate the effect of a ZEV mandate requiring 30% ZEV sales by 2030, over the decade from 2020 to 2030 in Canada (Fig. 1.1). AUM endogenously represents multi-year foresight for the automaker, including decisions about: (i) increasing ZEV model variety, (ii) intra-firm cross-price subsidies, and (iii) investing in R&D to reduce future ZEV costs. I find that of the three compliance mechanisms modelled, intra-firm cross-price subsidization dominates as the mechanism to comply with the ZEV mandate – that is, the automakers offer ZEVs at discounted prices to achieve higher ZEV market share, and charge a premium for conventional vehicles. I also find that the ZEV mandate could reduce auto industry profit by 7% to 44% in 2030 (relative to the baseline in the same year), mostly due to reduced vehicle sales in total, though overall profits still grow year-on-year from 2020 to 2030 (Fig. 1.2).

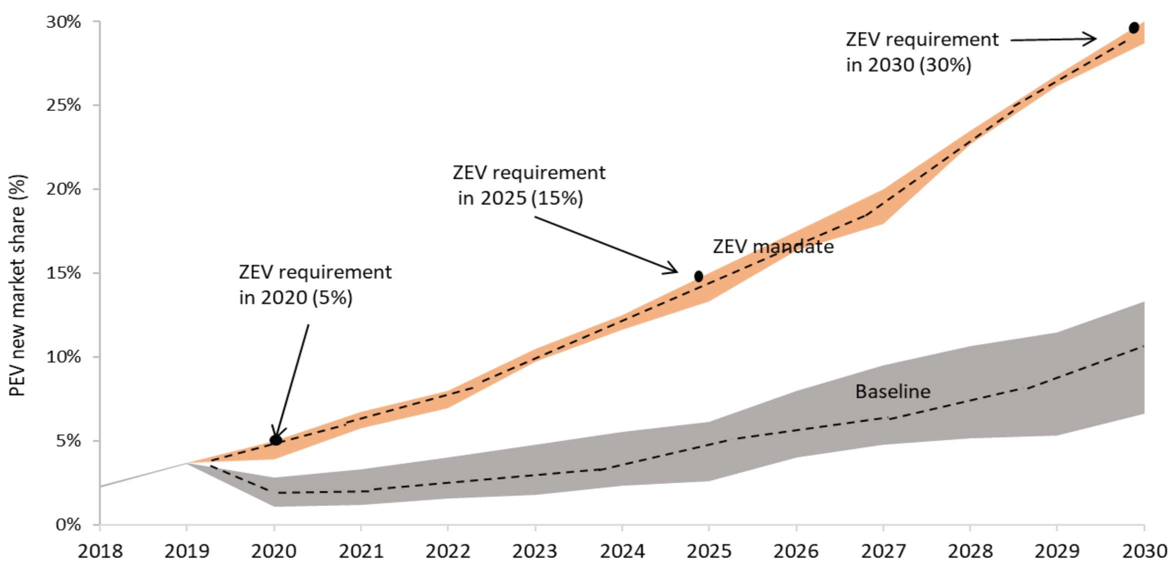

Fig. 1.1 ZEV new market share under policy scenarios (with shading representing uncertainty in parameters)

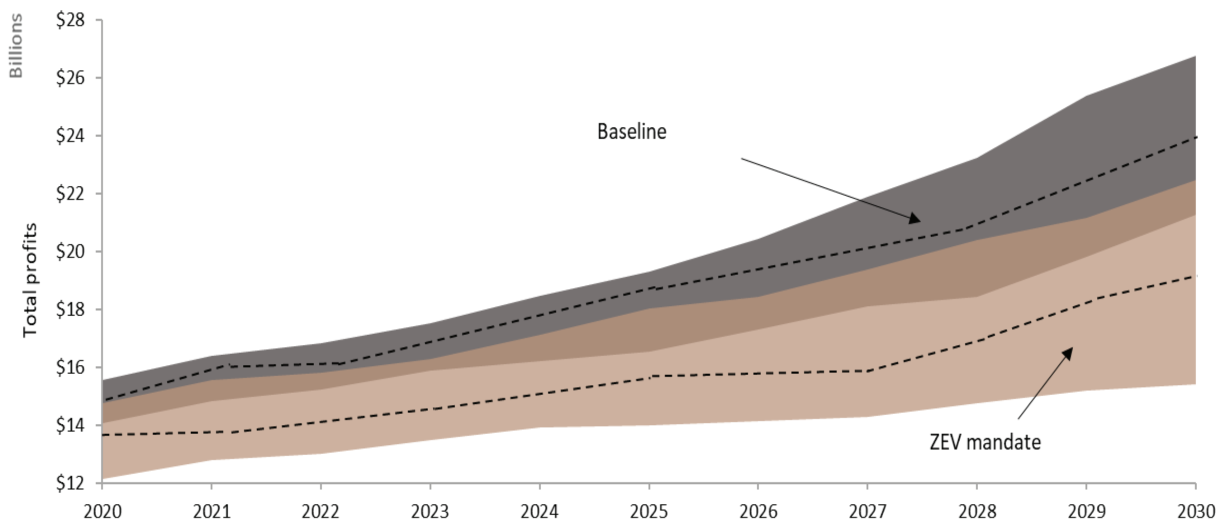

Fig. 1.2 Automaker profits (total) under the Baseline and ZEV mandate policy scenarios. The dotted line indicates the median case, and the shaded regions represent uncertainty in results.

My third goal (chapter 4) extends upon the first and the second goal to examine policy design in greater depth. Specifically, I examine how changes in more nuanced design features can affect the overall impact of the policy. As with my first modeling study, I use AUM to explore the case of a ZEV mandate in Canada requiring 30% ZEV sales by 2030. I compare three design features of the ZEV mandate, in terms of market uptake of ZEVs (specifically, achievement of the 2030 sales goal), consumer surplus and automaker industry profits. The design features I consider are: (i) changes in ZEV mandate penalty fee for non-compliance; (ii) alternative versions of ZEV mandate credit system; (iii) option of banking of credits. I find that a higher penalty for non-compliance (CAD$ 10k per credit) is needed to achieve the 2030 policy target of 30% new ZEV market share, while a lower penalty (CAD $2.5k -7.5k per credit) results in 14-26% market share by 2030 (Fig. 1.3). Compliance is further impacted by the ZEV credit scheme. For example, if plug-in hybrid vehicles earn the same credits as battery electric vehicles, ZEV market share is typically higher. Finally, allowing automakers to bank credit softens the policy impact on profits and increases automaker compliance in initial years. Results help to identify tradeoffs in policy design, such that achieving ZEV sales goals will come at the expense of reduced automaker profits and consumer utility (when excluding social benefits due to GHG mitigation and local air pollution)

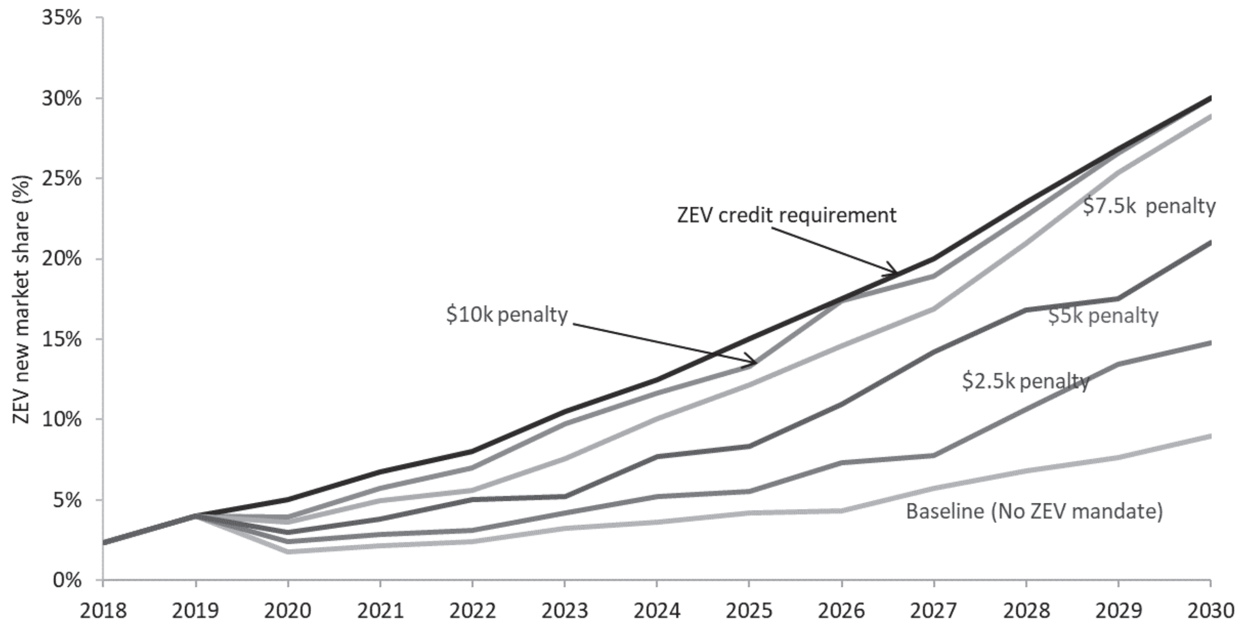

Fig. 1.3 ZEVs new vehicle market share in Canada under the Baseline and ZEV penalty scenarios (all with Equal credit scheme)

My fourth research goal (chapter 5) builds on the first goal of examining policy mixes, using the AUM model to quantitatively compare the effectiveness and cost-effectiveness of various policy mixes. Specifically, my research objectives are to compare several policies in terms of effectiveness (reaching 2030 GHG mitigation goals) and mitigation costs, namely: (i) a carbon tax; (ii) a vehicle emission standard (or VES); (iii) a zero emissions vehicle (ZEV) mandate, and (iv) combinations of all three at alternative stringencies. I find that on comparing individual policies (Fig. 1.4), the regulations are at least three times more expensive (expressed in $/tonne) than the carbon tax. For the tax, costs (in $/tonne) increase with increasing stringency, such that a $350/tonne tax is 20% (or $34/tonne) costlier than a $50/tonne tax. Among the regulations, for the VES, increasing stringency displays a U-shaped curve effect on cost-effectiveness. The VES is cheaper than a ZEV mandate at lower stringencies, but at higher stringencies the two are similarly efficient (both incentivize widespread ZEV deployment). In policy mixes (not shown), cost-effectiveness is improved by a carbon tax. Specifically, inclusion of a $100-150/tonne tax can achieve targets while being 30% to 50% less costly than a regulation alone.

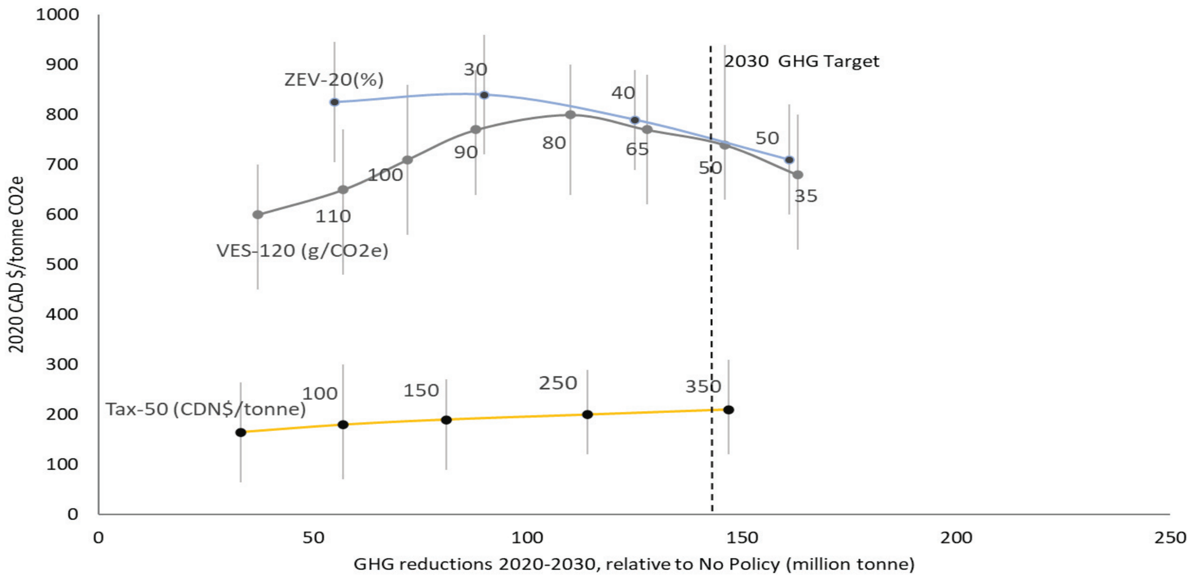

Fig.1.4 Change in the cost effectiveness of individual policies with increasing policy stringency, plotted against the corresponding GHG reductions (X-axis).

Roadmap of the thesis - This thesis follows a paper format such that each substantive chapter of the study is in the form of an individual, publishable paper. The structure of my thesis is as follows. The first two papers are presented in chapters 2, and 3 as they were published in *Transportation Research Part A: Policy and Practice,* and *Transportation Research Part D,* respectively. The third paper is presented in chapter 4 in the format required by *Transport Policy,* where a *Revised and Resubmitted* version is being considered for publication (as of May 2021). The fourth paper is presented in chapter 5 in the format required by *Ecological Economics*, where it is currently under review. Chapter 6 summarizes the key findings from the four papers and describes several policy recommendations that emerge from my research.

Chapter 2. Why have multiple climate policies for light-duty vehicles? Policy mix rationales, interactions and research gaps[3]

Abstract

Globally, there are a wide variety of policies in place that could help contribute to deep greenhouse gas (GHG) emissions reductions in the light-duty vehicle sector. Most regions are impacted by a mix of such policies. However, the transportation literature has devoted little attention to policy mixes, especially in the light-duty vehicles sector, so here we review and draw insights from the broader, mostly non-transport literature. We identify several rationales for pursuing mixes of policies: i) the “three legs” approach to transport decarbonization, namely that different policies should address different GHG reduction areas (low-carbon fuels, vehicle efficiency and reduced travel demand), ii) the “market failure” perspective that a different policy is needed to correct each market failure, iii) the “political process” perspective that considers the real-world need for a policy mix to be perceived as political acceptability, and iv) the “systems” perspective that policy needs to send signals to channel technological innovation and break the lock-in of incumbent practices. Based on this review, we develop a simple framework for examining policy interactions across multiple criteria, namely GHG mitigation, cost-effectiveness, political acceptability and transformative signal. We demonstrate this framework by setting hypotheses for interactions across six light-duty vehicle policies in the case of British Columbia, Canada – including a carbon tax, electric vehicle purchase incentives, infrastructure deployment and three regulations. We conclude with a summary of important research gaps, and implications for policy design as well as quantitative modeling.

[3] This paper was published as Bhardwaj, C., Axsen, J., Kern, F. and McCollum, D., 2020. Why have multiple climate policies for light-duty vehicles? Policy mix rationales, interactions and research gaps. Transportation Research Part A: Policy and Practice, 135, pp.309-326. Drs. Axsen, McCollum, and Kern helped in the writing (review and editing) of this paper, while also guiding me during the conceptual design stage.

2.1 Introduction

Many nations and regions have implemented climate policies to achieve greenhouse gas (GHG) emissions reductions among light-duty vehicles. Further, many regions are under the jurisdiction of multiple climate policies. For example, the light-duty vehicle sector in the Canadian province of British Columbia is impacted by a national vehicle emissions standard, a carbon tax, a low-carbon fuel standard, a zero-emissions vehicle (ZEV) sales mandate, ZEV purchase incentives, and various initiatives that support electric vehicle charging infrastructure. An even longer list of potential policies and strategies can be drawn from the literature (Geels, 2012; Melton et al., 2017; Sims et al, 2014). This paper explores the rationales, interactions and research gaps for such policy mixes for transportation, focusing on GHG mitigation goals for light-duty vehicles.

Despite the prevalence of policy mixes (Borrás and Edquist, 2013), surprisingly little transportation research has been devoted to the concept (Givoni et al, 2013), with little exploration of rationales for such mixes for light-duty vehicles. Many studies consider only one policy type in isolation. When a climate policy mix is considered, it is typically implied that each added policy has an additive effect on the GHG mitigation goal (e.g., Sperling and Eggert, 2014; McCollum et al, 2018). For example, there might be an expectation that the combination of a ZEV purchase incentive and charging infrastructure deployment policy will have more impact than either policy alone. Several studies also consider how multiple policies might lead to more cost-effective abatement, for example where the presence of a fuel tax might improve the efficiency or welfare impacts of a fuel economy standard (Small, 2012). However, the literature is generally silent regarding other rationales or motivations for the design of policy mixes. For example, it is possible that offering a ZEV purchase subsidy might make the implementation of a ZEV sales mandate more palatable to automakers – thus improving the political acceptability of the policy mix. It might be desirable to add such a policy to a policy mix, even if it does not induce further GHG mitigation, nor improve cost-effectiveness, if the resulting policy mix might have a greater probability of being implemented in the first place (Givoni et al., 2013).

In short, policy mix research is limited for transport, and especially so for the case of climate mitigation for light-duty vehicles. Important questions remain unaddressed, such as: why have a policy mix in the first place? What policies should be included? And how to design a “good” policy mix? In the realm of transport-energy modelling for the purposes of developing emissions scenarios, the treatment of policies and policy mixes has remained rather simplified.

However, research on policy mixes has grown more rapidly in other energy-related literatures (e.g. Lehmann and Grawel, 2013; del Río González, 2007; Del Rio, 2014; Rogge et al, 2017), as well as other fields of studies such as policy studies (Howlett and Rayner, 2007), economics (Oikonomou and Jepma, 2008), and innovation studies (Flanagan et al, 2011; Rogge and Reichardt, 2016). Because the terminology is quite varied, we start with some definitions to guide this paper:

1. We presently use “policy mix” as the more general and descriptive term, describing multiple policies that are implemented in the same country or region during the same time period, relating to the same overall societal objective (in our case, GHG emissions abatement). We acknowledge that others have provided more sophisticated definitions, such as Rogge and Reichardt’s (2016) conceptualization that includes policy processes and policy interactions as a part of the extended policy mix concept.
2. A “policy package” describes a more idealized, technocratic approach leading to an optimal combination of policies (Givoni et al, 2013), which some critique as not being a realistic option in most circumstances (Kern et al, 2017).
3. “Policy layering” (or stacking) describes a more haphazard approach to policy mixes, which are often developed over time, without careful deliberation or evaluation. New policy instruments are stacked onto previous ones when a policy window appears, without regard for potential interactions between policies or processes (Kingdon, 1984; Howlett and Rayner, 2013). This is how policy making often evolves in the real world (Howlett, 2004).
4. Finally, “policy patching” recognises the limitations of real-world policy making but attempts to design a “reasonably good or suitable” policy mix that can reach a degree of complementarity and coherence within existing governance arrangements (rather than requiring idealized, typically fictitious, conditions) (Howlett and Rayner, 2013). As we discuss in this

paper, we find this concept to be helpful, where the aim is to increase the coherence of the mix which is hoped to increase the chances that policy objectives are met.

In this paper we aim to contribute to the literature on policy mixes specifically in the transport sector (especially for light duty vehicles). To that end, we review available literature largely from outside of transportation and then use the insights gained to develop a framework for informing transport policymakers, researchers and modellers. Specifically, our objectives are to:

(i) identify gaps in the transport literature regarding policy mixes;
(ii) review studies on policy mixes from various disciplines, drawing rationales for policy mix use and other key insights relevant to the transport literature;
(iii) propose a general framework to guide exploration (and hypotheses generation) regarding interactions between climate policies; and
(iv) identify critical research gaps to support the design and evaluation of policy mixes.

Our intention is to bring more attention to careful consideration of policy mixes in the transport sector, both for qualitative evaluation and for informing the analysis of policy scenarios for quantitative modeling.

As noted, we focus only on climate change mitigation goals—namely achieving deep reductions in GHG emissions over the long term (e.g., 80% below 1990 by 2050) to demonstrate rationales for policy mixes and our framework for policy design. Clearly, there is a much broader set of potential sustainable transportation goals, including improvements regarding air pollutant emissions, traffic congestion, social equity, and urban liveability. However, for simplicity (in an already complex topic) we do not presently consider these additional societal objectives in our review – though we believe that most or all of the concepts we consider would apply in those cases as well.

The organization of the paper is as follows. Section 2.2 reviews transport literature on policy mixes to identify gaps. Section 2.3 reviews literature across various fields of studies to find justification for use of policy mixes and other relevant insights. Section 2.4 draws from this literature to propose a broad framework that would apply to policy mixes. Section 2.5 considers policy interactions in more detail, setting hypotheses for interactions among six policies for the illustrative case of

British Columbia, Canada. Section 2.6 summarizes, and concludes with critical research gaps.

2.2. Gaps in transport policy mix literature

The majority of the transport literature on climate or energy policy has studied policy instruments in isolation. As examples, studies focus solely on a carbon or fuel tax (e.g., Bruvoll and Larsen, 2004; Sterner, 2007; Mabit, 2014), fuel economy standards (e.g., Plotkin, 2009; Klier and Linn, 2010), or low-carbon fuel standards (e.g., Yeh and Sperling, 2010). There is a smaller set of transport-based studies that evaluate multiple policies, including those that focus on interactions between two particular policies (e.g., Whistance et al., 2017; Jenn et al., 2019a) and those that simulate broader policy mixes in efforts to achieve deep GHG mitigation targets (e.g., Lepitzki and Axsen, 2018; Wolinetz and Axsen, 2017; Yang et al, 2017;Greene et al, 2014; Yang et al, 2015; Rafaj et al, 2006). Of those studies that explore policy mixes, most do not provide a clear rationale for the specific mix of policies selected in the first place, including the types and stringencies of policies. In many cases, it seems that policy mixes are selected simply because they were already implemented in some jurisdictions or because the combination is thought to mitigate the unintended effects from a particular policy, such as rebound effects (e.g., Lah, 2015).

Some argue that an evaluation of policy instruments may not be considered complete without analysing the potential interactions between the constituent instruments (Flanagan et al, 2011). A few transport studies do study some interaction effects of policy mixes, though they usually focus only on policy effectiveness. For example, studies look at how a variety of policies might interact with a ZEV mandate in achieving GHG reduction goals (Sykes and Axsen, 2017), or similarly for a low-carbon fuel standard (Holland et al, 2009; Whistance et al, 2017; Lepitzki and Axsen, 2018). A few studies examine how different policy combinations can improve the cost-effectiveness of GHG mitigation in the light-duty vehicle sector (Small, 2012; Fox et al, 2017). However, such studies again provide little rationale for the policy mixes they select for their policy scenarios, and do not consider a broad set of evaluation criteria (beyond GHG impacts and cost-effectiveness).

There are several transport studies that discuss the notion of policy mixes and the need for integrated policy making, including several focused more on city-level goals such as air pollution, land use, noise, accidents, safety, and congestion (May and Roberts, 1995; May et al, 2006; Shepherd et al, 2006), as well as GHG mitigation (Stanley et al, 2018). Such discussions generally do not consider national or state/provincial level analyses (Jaccard et al, 2019). Moreover, theses policy mix studies also tend to focus only on optimizing a single objective (e.g., emissions reduction in Stanley et al, 2018). Several studies propose a slightly broader framework for policy mix design, by adding consideration of cost-effectiveness (e.g., Givoni et al, 2013; Givoni, 2014; Justen et al, 2014a; Justen et al, 2014b; Dijk et al, 2018). Further, these studies focus on idealized "policy packages" (as we define above), being optimally designed combinations of policy instruments, typically disconnected from real-world policy making. Justen et al (2014a) for example, acknowledge that actual policy processes may be quite different from what is recommended as an ideal policy package in their study. Real-world policy implementation is typically constrained (or at least impacted) by the policies already in place, the political acceptability of different policies among interest groups and the public, and the particular policy "windows" that might be open at a given point in time (Flanagan et al, 2011; Howlett and Rayner, 2013).

In short, the transport literature is missing a broader, real-world perspective on policy mixes (Marsden and Reardon, 2017), particularly on how to develop a light-duty vehicle climate policy mix that satisfies multiple objectives. The next section turns to the broader energy policy literature to look for insights that can inform transport policy analysis.

2.3. Different perspectives and rationales regarding policy mixes

Due to the dearth of transport-specific literature on this subject, we draw perspective on policy mixes from broader literatures on energy and environmental policy. Our approach is largely a narrative review, where we identify and categorize studies and perspectives based on what we discover in our literature search, as well as from the collective judgement of the author team. For more established literatures, it can be desirable to perform a systematic review or even a meta-analysis – however, a narrative review is more appropriate in cases like this (Sorrell, 2007; Sovacool et al, 2018). To identify potential articles, we used search terms such as "policy mixes", "policy combinations", and "policy packaging" in databases including Web of Science, JSTOR, Elsevier, and Google scholar. As a screening process we looked through the abstracts and tried to select articles that appear to discuss reasons for combining policies.

We organize this section by perspectives on policy mixes that emerged from this review, which largely correspond with viewpoints from engineering, economics, policy studies, and innovations studies. We briefly review each perspective here, including any insights regarding why and how to develop transport policy mixes.

2.3.1 The "three-legs" perspective

This first perspective is the most straightforward, and quite frequently used in the transportation literature. One might call it an engineering or technical perspective, as it focuses on the simple formula that total GHG emissions in the transportation sector are a function of the carbon intensity of fuel (gCO_{2e}/MJ), the fuel efficiency of vehicle usage (MJ/km), and travel demand (total vehicle km travelled) (Creutzig et al, 2011; Sperling and Eggert, 2014). Some refer to these as the individual legs of a "three-legged" stool, implying that a sound climate policy mix needs to address all three components or sub-sectors: fuel carbon intensity, vehicle efficiency and vehicle travel demand (e.g., Schäfer, 2005; Creutzig et al, 2011; Sperling and Eggert, 2014). The Intergovernmental Panel on Climate Change (IPCC) uses a version of this, though further separates travel demand into mode choice versus total passenger demand components (IPCC, 2014). Table 2.1 summarizes the "three legs", their working mechanism and how they may relate to policies in the light duty vehicle sector.

As exemplified by Sperling and Eggert (2014), California's broad and ambitious climate policy strategy for transportation is often described according to this rationale. Their policy mix includes a low-carbon fuel standard (cutting fuel carbon intensity), what were at one time more ambitious vehicle emissions standards than the broader US nation (though as of 2020 this may happen again), and a policy aimed at reducing vehicle travel demand in California's metropolitan regions (Senate Bill 375, via support for transit usage, urban density, active travel and/or mobility pricing). While such a comprehensive approach is compelling, there is no strong explicit rationale for why such a policy mix is needed. For example, the perspective does not explain why most or all of GHG reductions could not occur through just one leg, or two. Further, the perspective offers no guidance in the selection or evaluation of different policy mixes. How much weight should be placed on each "leg"? And how do we know if one policy mix is better than another?

Table 2.1 The "three legs of the stool" perspective

The "three legs"	Mechanism	Example for low-carbon light-duty vehicles
Leg 1: reduce carbon intensity of fuel (gCO_{2e}/MJ)	If grams of CO_2 released on burning per unit (MJ) of a fuel can be reduced, for example by shifting to a fuel with lower carbon intensity, the overall emissions from the light duty vehicle sector will reduce	Requires fuel-specific policies
Leg 2: improve efficiency of vehicle usage (MJ/km)	If efficiency of vehicles can be increased such that they consume lesser fuel for every kilometre driven, the overall emissions from the light duty vehicle sector will reduce	Requires policies that push for fuel efficient cars
Leg 3: reduce travel demand (total vehicle km travelled)	If travel demand reduces, such that people drive less, the overall emissions from the light duty vehicle sector will reduce	Requires policies that directly affect travel demand, typically by making travel more expensive

2.3.2 The "multiple market failures" perspective

The second perspective focuses on policies as a way to correct market failures, drawing from neoclassical economics. The traditional view in economics has favoured the use of single policy instruments to correct the environmental externality in question, most commonly a Pigouvian tax, or a carbon tax in the case of climate policy (Goulder and Parry, 2008; Lehmann, 2012). This view has led to the predominant economists' argument that climate policies other than a carbon tax deviate from the goal of cost minimisation or welfare maximisation (i.e., imposing a higher than necessary cost for the society).

More recently, some economists have expanded this market failure perspective to argue that the use of multiple instruments may result in an efficient or cost-optimal outcome in a "second-best" setting, that is, when multiple market failures exist in the system (e.g., Goulder and Parry, 2008; Fankhauser, 2010; Lehmann, 2012; Twomey, 2012). Bennear and Stavins (2007) explain the second-best theory (given in Lipsey and Lancaster, 1956) as follows: if several market failures (e.g., negative environmental externality, research and development spillover, and market power) exist, then pursuing the single best policy for the main goal (often a pricing mechanism) is not enough. Thus, additional policy instruments will be required to correct these additional market failures. Further, the "second best" theory also includes the idea that the ideal policy is often not possible (such as pricing), potentially due to lack of political acceptability. Some common light-duty vehicle sector related market failures are listed in Table 2.2.

Table 2.2 Examples of multiple market failures

Market failure	Mechanism	Example for low-carbon light-duty vehicles
Negative externality: Price does not represent true social costs	If the price of a commodity does not include full social costs, it may be used more than the optimal amount	Fossil fuels are cheaper because their price does not represent the true costs incurred by society due to pollution, causing them to appear more economical than alternative fuels
R&D spillover failure: Public good nature of technological innovation (Lehmann, 2012)	Once technology is created, it is difficult to prevent others from free riding on that knowledge. This may lead to under investment in research and development	Automakers may prefer to wait for competing firms to innovate alternative fuel vehicle technologies, thus delaying transition away from conventional vehicles
Oligopolistic market structure (Twomey, 2012)	Few big corporations may dominate the market and may indulge in strategic behaviour to prevent new firms from entering.	The difficulty in sustaining against the dominant conventional vehicle producers may discourage new entrants producing alternative fuel vehicles.

This multiple market failure rationale holds relevance for the transport sector. For example, a carbon tax might not effectively incentivize automakers to invest in research on alternative fuel vehicles in a timely manner, for example due to the anticipation of technological innovation spilling over to other automakers (Azar and Sanden, 2011; Lehmann, 2012). Consequently, a carbon tax may need to be supplemented by another policy instrument (e.g. R&D subsidies) that can address this knowledge spillover market failure. In short, a "multiple market failures" perspective makes a case for developing policy mixes, where one policy instrument may be included to correct for each identified market failure (Jaffe et al, 2005). Yet, despite the usefulness of the economics literature to the policy mix context, some limitations can be observed. In particular, there is the often-exclusive focus on cost minimization (or welfare maximization) as a policy evaluation criterion, which some argue is too idealistic (Howlett, 2004). This perspective tends to ignore or over-simplify real-world policymaking; for example, neglecting consideration of which policies might be more politically acceptable or administratively easier to implement, and thus ignoring the corresponding policy processes (Kern and Howlett, 2009), which we address next.

2.3.3 The "political process" perspective

In contrast to the first two perspectives, researchers in policy studies tend to more systematically examine the complexity of real-world policymaking, and often present a more nuanced view of the process of instrument choice and policy design (Howlett and Rayner, 2013; Rogge et al, 2017). Relating to policy mixes, Del Rio and Howlett (2013) suggest that complex problems involving complex arrangements (e.g., multiple governance levels and policy actors) naturally lead to the implementation of policy mixes to address a given policy problem. In short, the use of policy mixes is often, in part, an imperfect result of complex systems that often involve multiple actors.

One of the key takeaways emerging from policy studies is the need to consider political acceptability when designing policies. While certain authors like Deroubaix and Leveque (2006) distinguish between social acceptability and political feasibility, we use the term political acceptability to refer to the general notion of acceptability, includes acceptance of the policy among the general public (socially acceptable) and among special interest groups and polity (political feasibility). Political acceptability is thus affected by citizens' support or opposition to a policy, as well as by the acceptability of the policy amongst other key stakeholders (e.g., the auto industry and fuel suppliers in the case of transport). Literature describes this criterion according to the perceived "legitimacy" of the government, or social support for government actions– a lack of which will result in extra transaction costs (e.g. Givoni et al, 2013; Kern and Howlett, 2009; Howlett and Rayner, 2007). For example, even if a carbon tax is the most economically efficient policy from an economic perspective, the lack of political acceptability means that it is not often implemented – at least, in the vast majority of cases, not at a level that is stringent enough to induce deep GHG mitigation (World Bank Group, 2019). Political acceptability can also provide a rationale for policy mixes, and is sometimes connected to economists' "second best" theory – where a mix of policies is implemented because the ideal policy (often carbon tax or alternate form of pricing) is not politically acceptable.

Consideration of political acceptability can speak to the reality of "policy patching" in contrast to "policy packaging" (Howlett and Rayner, 2013; Kern et al, 2017). As noted in our introduction, policy packaging may be understood as a policy design process in which previous policies can be discarded and new policy mixes can be designed from scratch (i.e., from a blank slate). Such a process, effectively creating a "blank slate" for policymakers, is very rare (Pierson, 2000). In contrast, the notion of policy patching describes policymakers as needing to be more adaptive to current circumstances, and less ideologically-rigid (Howlett, 2004). There are numerous examples of such adaptations for individual policies in the transportation sector. For example, what are now framed as vehicle emissions standards in Canada and the US were originally implemented as a fuel efficiency policy in the 1970s (the Corporate Average Fuel Economy or CAFE standards), which have since been adjusted to also address air pollution, and more recently greenhouse gas emissions.

We interpret policy patching as the effort to increase the coherence of a policy mix, in how the policies interact and ultimately are able to collectively achieve the overall objectives. Often, policymakers in a given region might find it more politically plausible to amend an existing policy mix by strategically adding certain instruments rather than developing a brand-new policy mix. For example, while California's suite of climate policies is often touted as a complementary "package" (Sperling and Eggert, 2014), it is more fairly characterized as a "patchwork" as it includes some policies that have been changed repeatedly over time, and in some cases re-purposed, based on the changing needs of society.

This literature also brings up consideration of the equity and distributive impacts of policies (Lucas and Jonas, 2012; Litman and Burwell, 2006; Allen and Faber, 2019). Some consider equity to be an important criterion for policies, such as addressing inequalities in vehicle ownership (Thomopoulos et al., 2009), as well as transport accessibility and proximity to transport infrastructure (Litman, 2002; Eliasson and Mattson,2006; Pereira et al 2017). Given our present focus on policy mixes for GHG mitigation, equity is often framed according to the distribution of policy costs across different household income levels (Cullenward et al, 2016), where a policy may be considered regressive or inequitable if it disproportionately increases expenditures of lower income households. Such evaluations can also be conducted from a welfare economics perspective (e.g., DeShazo et al., 2017). Despite the potential importance of maintaining social equity impacts as a unique policy criterion, we presently follow the lead of a number of authors that suggest that perceptions of equity and fairness are strongly connected with political acceptability (e.g., Jaensirisak et al, 2005), where equity issues could be grouped within the criterion of political acceptability (e.g. Viegas, 2001; Schade and Schlag, 2003; Turcksin et al., 2011).

While the policy studies literature provides useful insights, it can be critiqued for focusing too heavily on policy and government processes and other influences such as infrastructural and institutional factors in the system (Foxon and Pearson, 2008). Further, most concepts are described and analysed in a qualitative context, with operational definitions sometimes left unclear (Rogge and Reichardt, 2016). As quantitatively inclined readers may appreciate, this limitation complicates the ability to translate insights into quantitative analyses, such as policy simulation modelling. For example, how does one parameterize the political acceptability of a policy, while seeking to simulate the policy's GHG emissions impacts and welfare costs?

However, we argue that, while often difficult to quantify, some of the concepts that flow from policy studies are still very relevant to quantitative transportation research, especially policy modelling. Most directly, appreciation of the policy environment, the policy patching process, and political acceptability can all influence the design of policy scenarios used in modelling studies, such as the policy instruments, mixes and stringency levels selected by the modeller. At the very least, it seems that such factors should be explicitly explained by researchers when they select their modelling scenarios – even if this explanation can only be done at a qualitative level.

2.3.4 The innovation systems perspective

Finally, the field of innovation studies offers perspectives on the broader system, considering more than just policy instruments and policy processes. This approach "emphasizes that innovation is a dynamic process, arising out of interplay between different actors, and involving both knowledge flows and market interactions” (Foxon and Pearson, 2008 pp S150). This systems perspective includes the technological considerations, market failures and policy processes noted above, and adds the explicit consideration of institutional factors (e.g., regulatory frameworks, market structures), infrastructural factors (e.g., charging stations), and lock-in mechanisms (e.g., economies of scale, network effects) that may support incumbent technologies and pose barriers for innovations.

Helpfully, numerous studies in innovation studies have identified a variety of categories of systemic failures that policy can help to rectify (e.g. Smith, 2000; Foxon and Pearson, 2008; Borrás and Edquist, 2013; Weber and Rohracher, 2012). Weber and Rohracher (2012) in particular provide a useful summary of structural system failures and transformational failures (Table 2.3), in addition to the market failures noted by the economics perspective (Table 2.2). The structural system failures relate more to innovation performance of the system while transformational failures aim to capture the fundamental character of the system in the longer-term (Weber and Rohracher, 2012). Several of these failures may be particularly relevant for transitions in the light-duty vehicle sector, including:

- **Infrastructure failures** relate to difficulties in establishing new, effective recharging or refueling infrastructure for alternative fuel vehicles.
- **Network failures** describe how innovation and supply systems become “locked-in” to the incumbent technology. For example, societal lock-in to “automobility” has been described as being a function of the entrenchment of current automakers, parts providers, dealerships, and oil companies, as well roads, refueling infrastructure and service facilities (Urry, 2004).
- **Institutional failures** explain how a given region might lack the agencies or institutions needed to design, implement, enforce, update, and adapt strong climate policy – for example where California’s effective leadership in climate policy may be partially explained by its unique and long-established Air Resources Board (CARB) (Sperling and Eggert, 2014).
- **Directionality failures** explain the lack of “shared vision” or agreement among stakeholders as to which low-carbon fuels and vehicles society should or will transition towards, be they powered by electricity, hydrogen, biofuels or another fuel, which captures the observed cycles of “hype and

disappointment" for different fuels over the past several decades (Melton et al, 2016).

- **Reflexivity failures** describe the inability of a transition to adapt to changing conditions, such as progress in low-carbon technologies like automotive batteries –in that institutional capacity would be needed to design and adapt such climate policies.

Weber and Rohracher (2012) acknowledge that more research is needed to establish whether all failures are problems or not, and what implications they hold for policy design. For example, one might perceive this as an extension of the market failures perspective, where one policy is needed to address each relevant failure (be it, market, structural, or transformation). Usefully, this perspective highlights the point that there exist multiple failures or barriers across a system, facing more challenges than has been articulated in conventional economics or policy studies. Such failures may provide added rationale for implementing a mix of policies that address different areas -- connecting back to the "three legs" perspective. For example, one might argue that while a sufficiently high carbon price could address environmental externalities and R&D subsidies could address spillover effects, additional policy may still be needed to create enough momentum and "directionality" to break the lock-in of incumbent technology. Specifically, some technology-forcing or phase-out policies, such as the low-carbon fuel standard and zero-emissions vehicle mandate, could serve an added role by providing such "directionality" to the system (Kivimaa and Kern 2016; Fox et al, 2017).

In short, while this list of failures helps to broaden the other perspectives summarized above, it is not yet straightforward to translate these insights into the design of a policy mix in a specific situation. Rather, Weber and Rohracher (2012) establish a framework with blanks that still need to be filled in – or hypotheses to explore. The perspective also offers little specific consideration of policy interactions, and lacks easily quantifiable or operationalized concepts (Foxon and Pearson, 2008; Rogge and Reichardt, 2016). There is also some conceptual ambiguity (and overlap) among the various types of failures in Table 2.2. This, again, makes it difficult to translate insights directly from innovations literature into policy modeling or other quantitative research (Turnheim, 2015).

Table 2.3 List of failures across the system that justify policy mixes (following Weber and Rohracher, 2012).

Type of failure	Failure mechanism (quotations from Weber and Rohracher, 2012; pp 1045)	Example for low-carbon light-duty vehicles
Structural system failures		
Infrastructural failure	"Lack of physical and knowledge infrastructures."	Challenges in deploying and coordinating widespread charging and refueling infrastructure.
Institutional failures	"Lack of regulatory frameworks or market structures (e.g. intellectual property rights) or social norms and values that hinder innovation."	Absence of strong or stable institution or enforcement agencies, making it difficult to implement, update or adjust stringent policy (e.g., technology standards).
Interaction or network failure	"Cooperation in closely tied networks leads to lock-in into established trajectories and a lack of infusion of new ideas."	Network interactions have developed that lock-in to incumbent technology (conventional, gasoline-powered vehicles), including networks of automakers, ancillary part supply chains, car dealerships and fuel suppliers.
Capabilities failure	"Lack of appropriate competencies and resources at actor and firm level prevent the access to new knowledge."	Workers trained to manufacture conventional vehicles may find it difficult to learn new technical skills.
Transformational system failures		
Directionality failure	"Lack of shared vision regarding the goal and direction of the transformation process."	Confusion and inconsistencies among stakeholders in regards to the direction of a low-carbon, alternative fuel transition, for example, be it towards electric vehicles, hydrogen, biofuels, or natural gas.
Demand articulation failure	"Insufficient spaces for anticipating and learning about user needs to enable the uptake of innovations by users."	A consistent lack of shared understanding of consumer perceptions of, and potential demand for, low-carbon vehicles, or fuel-efficient vehicles.
Policy coordination failure	"Lack of multi-level policy coordination across different systemic levels (e.g. regional–national)."	Lack of coordination or strategy in national-, state-, and metropolitan-level policy mixes, such as how state-based regulations (e.g., a zero-emissions vehicle mandate) might interact with nation-based regulations (e.g., vehicle emissions standards).
Reflexivity failure	"Insufficient ability of the system to monitor, anticipate and involve actors in processes of self-governance."	The difficulty of trying to update technology-specific regulations (e.g., a zero-emissions vehicle mandate) according to technological progress (e.g., reduced cost of automotive batteries).

2.3.5 Insights and implications for light-duty vehicle climate policy

A number of key insights can be drawn from these perspectives regarding frameworks and guiding principles for designing policy mixes for the light duty vehicle sector.

i. The above literature review, in our view, has provided a convincing argument that use of policy mixes is an appropriate strategy and is well supported across a range of disciplines.

ii. Almost all policy mix frameworks (e.g. Oikonomou and Jepma, 2008 in economics; Howlett and Rayner , 2007;2013 in policy studies; Borras and Edqvist, 2013; Foxon and Pearson, 2007; Rogge and Reichardt, 2016 in innovation studies) emphasize the need for identifying policy objectives and considering policy instruments as tools for meeting those objectives, as well the importance of examining interactions between constituent policy instruments.

iii. Literature discusses diverse types of policy design approaches. Some studies recommend a "policy packaging" approach where each policy mix is carefully designed from scratch (Givoni et al, 2013). While others recommend a more nuanced "policy patching" approach, where an attempt is made to build on the existing policy mix and to complement existing instruments or improve the stringency, coherence, etc of the mix by adding or removing individual instruments (Howlett and Rayner, 2013).

iv. It is often recommended that policies be evaluated across multiple objectives or criteria (Oikonomou and Jepma, 2008; Rogge and Reichardt, 2016), with each disciplinary perspective favouring different objectives e.g. effectiveness (technical), economic efficiency (economics), political acceptability (policy studies) and transformative signalling (innovation studies).

v. Policy mix literature collectively identifies a range of failures (market, structural and transformative) that may provide guidance and criteria for designing policy mixes for the light duty vehicle sector.

2.4. Proposing a framework for policy mix interactions

In an effort to integrate and build upon the literatures summarized above, in this section we propose a framework to help guide the setting of hypotheses for policy interactions, and identification of important research gaps relating to policy mix design. In these considerations, we borrow from multiple studies reviewed above, but in particular attempt to simplify Rogge and Reichardt (2016)'s extended policy mix concept. As a starting point, we continue with the concept of policy patching to describe the process of instrument selection, borrowed from policy studies (Howlett and Rayner, 2013; Kern et al., 2017).

While this present exercise is qualitative, we note that the framework could also help to inform and improve quantitative modeling, and identify other gaps where additional quantitative data collection and analysis is needed. We think of this framework as thus complementing or informing, rather than acting as substitutes for, more detailed transport scenario modelling exercises. In particular, while modelling exercises provide a detailed method for evaluation of transport policy mixes, the following discussion can present a way of arriving at a smaller, more specific set of instruments which can then be subjected to the rigorous quantitative analysis (e.g. as suggested in Givoni et al, 2013).

In a complex world, policymakers inevitably need to consider multiple objectives (or different evaluation criteria for the same objectives) for a given policy. Different stakeholders in a democratic institutional setting may assign different yardsticks for the same policy. There is some debate in the literature over which criteria to include, which of course will influence the selection of a preferred solution (Turcksin et al, 2011). As noted, for this paper our assumed primary objective is GHG emissions abatement, notably the long-term goals of deep decarbonization which is often operationalized as an 80% reduction by 2050, relative to 1990 levels. We draw from the four perspectives identified in our literature review above to construct four broad criteria of policy mix interactions: (a) effectiveness at GHG emissions abatement, (b) economic efficiency or cost effectiveness, (c) political acceptability, and (d) transformative signaling. These are depicted in the row headings of Table 2.4. Here we briefly discuss each criterion, including the challenges involved in evaluation.

Similar to Oikonomu and Jepma (2008), we simply define "effectiveness" as the likelihood that the policy will help the policy mix contribute to a specific environmental objective. Here we mean the additive contribution of the policy to tonnes CO_2e mitigated by 2030 or 2050. Such a goal is most concerned with the aggregate impact on GHG mitigation, ideally at well-to-wheel (WTW) perspective, including the upstream GHG emissions from fuel production (or electricity generation). It can also be helpful to break down impacts by the "three legs", that is, GHG reductions from reduction of the carbon intensity of fuels (gCO_2e/MJ), improved vehicle efficiency (MJ/km), or reduced vehicle travel (km or VKT). However, this criterion does not imply any particular weighting or importance across these three legs. To quantify the additive GHG effects of a given policy to a policy mix, simulation modeling is often required or recommended (see reviews by Sovacool et al, 2018 and Justen et al, 2014b). However, realistic simulation of a policy mix requires a model that is well-suited to simulate each policy in question, which can be a challenge – potentially requiring realistic simulation of decisions by agents as diverse as consumers, automakers and fuel providers.

Table 2.4 Framework for evaluation of policy interactions (climate policies for light-duty vehicles)

Policy interaction criterion	Explanation	Quantitative measure	Sub-components	Quantitative data availability and challenges
1) Effectiveness at GHG mitigation	Does the policy lead to additional GHG mitigation?	Tonnes CO_2e abated, in a given year, e.g., 2030 or 2050 (ideally well-to-wheel or full Life Cycle Analysis)	Can be evaluated in aggregate, or split by "Three legs": 1. Carbon intensity of fuel (gCO2/MJ) 2. Vehicle efficiency (MJ/km) 3. Vehicle usage (VKT)	Requires modeling, such as simulation, optimization, or technology-adoption models. Challenges: for interactions, model needs to be equipped to realistically simulate multiple policies – including consumer and industry behaviour. Model also needs to simulate long-run dynamics in behaviour and technology.
2) Cost-effective	Does the policy improve (or worsen) the cost-effectiveness of the policy mix?	$/Tonne CO_2e abated, or consumer utility	Can be evaluated in aggregate (total social welfare), or broken down, e.g., by: 1. Consumer utility 2. Industry profit 3. Government expenditure 4. General equilibrium impacts	Requires modeling suited to the measure of cost-effectiveness. Partial-equilibrium models can be used to simulate utility, profit or government expenditure impacts. General-equilibrium models (e.g., CGE) are needed for broader impacts. Challenges: Few transport studies do this for long time horizons. Modeling has many of the same challenges as for effectiveness, with added complexity of efficiency measures.
3) Political acceptability	Does the policy improve (or worsen) the political acceptability of the policy mix?	Not as clear. Percentage of citizens or stakeholders that support or oppose the policy? Directly ask the perceptions of the policymaker?	Can be split between citizens and special interest groups. May need to focus on interest groups with particular clout in a particular context (e.g., automakers in a region with more auto-related manufacturing).	Public acceptability can be assessed through "polling" or representative surveys of the public, while interest groups can be studied via stakeholder interviews. Challenges: existing data is sparse, and acceptance can vary by region, over time, and by context. Stakeholder's in particular might provide "strategic" responses in interviews.
4) Transformational signal	Aside from the above factors, does the policy provide an added "push" in transition towards the low-carbon goal?	Unclear how to quantify in general. Specific measures could be dollars invested in R&D activity, or number of patents or prototypes per year. Infrastructure can be measured by density (relative to gasoline/diesel equivalent).	Can draw from Weber and Rohrachers's (2012) framework, including: 1) Signal for R&D investment 2) Provision of physical infrastructure 3) Break "lock-in" 4) Pathway directionality	Some components can use existing models, including technological change models (for R&D investment), or technology adoption (for charging). Systems dynamics models Challenges: lack of existing models or data, complex dynamics.

The second criterion is cost-effectiveness, which we take from the common economics definition of minimizing GHG mitigation costs ($/per tonne CO_2e). Studies vary widely in terms of focus on impacts to consumer utility (Greene et al, 2014), to automaker profits (Jenn et al, 2019b), to government expenditures (Axsen and Wolinetz, 2018), or to broader "social welfare" (e.g., Small, 2012). Simulation of policy interactions regarding cost-effectiveness faces many of the same modelling challenges as for simulation of GHG impacts, including challenges and uncertainties in long-term dynamics in consumer and industry behaviour (Greene and Ji, 2016). We also note that some economists use models to simulate the "optimal pollution" level via a cost-benefit analysis (e.g. Nordhaus, 1991) – though that is not our current intent.

Third, drawing from policy studies, our framework includes political acceptability, which is in part determined by political capital possessed by the affected actors (Justen et al, 2014a). As noted earlier, our definition of the political acceptability criterion includes both acceptability by citizens (or the public) and amongst special interest groups (e.g. auto industry). Moreover, we assume our definition of political acceptability to include perceptions of equity issues (acknowledging that equity impacts could rightly be a separate policy evaluation criterion). Public acceptance can be measured through surveys of representative samples (Eriksson et al, 2008; Bristow et al, 2010; Rhodes et al, 2017), though stated acceptance can vary substantially by region, and in a given region over time. Stakeholder acceptance can be more difficult to assess, especially among regulated agents that might have a reason to "strategically" support or oppose particular policies that will impact them – for example, industry may want to over-represent their costs of compliance with an environmental policy. Further, while stakeholder interviews can provide some insights, in many cases interactions between stakeholders and government officials take place behind "closed doors".

Finally, we draw from innovation studies to consider the transformative signal provided by the added policy – integrating several concepts summarized by Weber and Rohracher (2012). Specifically, we consider the sub-components of the added policy's potential to: i) induce research investment in relevant technologies (Borras and Edqvist, 2013), ii) increase the availability of supportive physical infrastructure

(Foxon and Pearson, 2008), iii) overcome lock-in effects to the status quo (Smith, 2000), and iv) provide directionality in terms of the direction of the transition pathway (Weber and Rohracher, 2012). These transformative signals, often overlapping in impact, can work together to shift the incumbent system out of its lock-in (e.g., to gasoline powered internal combustion engines), and stimulate technological and social change. This criterion is admittedly difficult to quantify. Attempts can be made to track investment activity, though much of these data are private. Physical infrastructure (e.g., electric vehicle charging stations) can also be tracked, though it is unclear how much infrastructure is needed for a given GHG goal, or more specifically, a given level of electric vehicle deployment (Hardman et al, 2018). Further, directionality and lock-in effects are particularly complex to model, requiring consideration of numerous feedbacks in the system (Turnheim, 2015). Nevertheless, we believe that explicit consideration of these sub-criteria can help researchers and policymakers to better understand the broader impacts of a given policy mix, particularly those with long-term (i.e., multi-decade) goals where substantial system changes are required.

Our list is by no means comprehensive and it may be argued that we omit potentially important criteria. For example, while equity impacts could be represented as a unique criterion, we presently group it with our definition of political acceptability. Such simplifications are done for the sake of parsimony, and our framework may be extended to more carefully consider such additional criteria in future work.

2.5. Illustration of potential policy interactions: Hypotheses for the case of British Columbia, Canada

We illustrate our framework for assessing policy interactions using the case of British Columbia, Canada. While regions across the world have a wide array of unique climate policy mixes for light-duty vehicles, British Columbia includes six commonly discussed policy types (as of February 2020):

1. **A carbon tax** has been in place in British Columbia since 2008. The 2019 tax rate is $CDN 40 per tonne of carbon dioxide equivalent emissions, which will increase at the rate of $CDN 5 per year until it reaches $CDN 50 per tonne in 2021 (Government of British Columbia, 2019a).

2. **Purchase incentives** are available for consumers buying zero emission vehicles (ZEVs) such as plug-in hybrid, battery electric and hydrogen fuel cell vehicles. This program offers up to $CDN 5000 for the purchase of plug-in hybrid and battery electric vehicles and $CDN 6000 for the purchase of hydrogen fuel cell vehicles (Government of British Columbia, 2019b).
3. **The deployment ZEV charging infrastructure** is supported by the government according to several policies. For example, the DC Fast charger program has deployed 30 fast chargers along major highways in British Columbia. Moreover, the government offers subsidies to consumers who wish to install chargers at home or at work (Government of British Columbia, 2019b)
4. **A low carbon fuel standard (LCFS)** was implemented in 2008, which requires fuel suppliers to reduce the carbon intensity of the fuels that they supply into the market, either by selling low-carbon biofuels, or alternative fuels (e.g. electricity or hydrogen) or buying credits from other suppliers. British Columbia's LCFS now requires a 20% reduction in carbon intensity of transport fuels by 2030 (Government of British Columbia, 2019c).
5. **A vehicle emissions standard** or VES (what used to be called fuel economy standards, e.g. CAFE), is in place nationally, which requires automakers to reduce the average carbon intensity of their new vehicle sales (gCO_2e/km). For the last decade, Canada has followed the United States' VES in terms of stringency as well as timing (though as of 2020, Canada seems more likely than the US to stick to its 2025 requirements).
6. **A ZEV sales mandate** was implemented in 2019, which requires manufacturers to make a certain percentage of zero or low emission vehicles for sale. Initially implemented in California in 1990, the policy has more recently been legislated in China, and the Canadian province of Quebec. British Columbia's version now has the highest stringency and longest time horizon, requiring ZEVs to make up 30% of light-duty vehicle sales by 2030, and 100% by 2040.

As noted, the overall performance of the policy mix will be affected by how the constituent policy instruments interact in combination (May et al, 2006). To illustrate our framework, and to identify research gaps regarding policy mix interactions, we consider interactions between each pair of policies. We hypothesize interactions between policy measures to have either:

- {+} a positive interaction (i.e., the added policy improves evaluation for a given criterion);
- {0} no marginal impact; or
- {-} a negative interaction (i.e., the added policy decreases the evaluation of a given criterion).

Two or more policies can be considered as “complementary” on a given criterion if their combined evaluation would score more highly due to a positive interaction.

Our illustration is a purely qualitative exercise, where we set hypotheses for the general direction (“+”, “-“ or “0”) and strength (e.g., “+” or “++”) of expected interactions for each criterion. We generate hypotheses for these based on literature review, empirical evidence from other regions, and our own judgement. While simplistic, we believe this exercise demonstrates a number of potential considerations for the mixing of policies. Further, this type of exercise can be seen as an initial step towards more detailed quantitative analysis of one or more potential policy mixes. Our hypotheses are summarized in Table 2.5. The following subsections work through each policy, hypothesizing (where possible) potential positive or negative interactions that it would bring to the other five policy types.

Table 2.5: Hypotheses for potential policy interactions

	Carbon Tax	ZEV subsidy	Charger rollout	LCFS	VES	ZEV mandate
Adding…						
…a carbon tax						
GHG mitigation	n/a	++	++	++	++	++
Cost-effectiveness	n/a	+	+	+	+	+
Acceptability	n/a	--	--	-	-	-
Transformation	n/a	+?	+?	?	?	?
…a ZEV subsidy						
GHG mitigation	+	n/a	+	?	?	?
Cost-effectiveness	-	n/a	+	?	?	?
Acceptability	++	n/a	++	++	++	++
Transformation	+	n/a	+	+	+	+
…charger rollout						
GHG mitigation	?	?	n/a	?	?	?
Cost-effectiveness	-	-	n/a	-	-	-
Acceptability	+	+	n/a	++	++	++
Transformation	+	+	n/a	+	+	+
…an LCFS						
GHG mitigation	+	++	++	n/a	+	0/+
Cost-effectiveness	-	?	?	n/a	?	?
Acceptability	+	+	+	n/a	+	+
Transformation	+	+	+	n/a	+	+
…a VES						
GHG mitigation	+	++	++	+	n/a	+
Cost-effectiveness	?	?	?	?	n/a	?
Acceptability	+	+	+	+	n/a	+
Transformation	+	+	+	0	n/a	?
…a ZEV mandate						
GHG mitigation	+	++	++	0	+	n/a
Cost-effectiveness	-	?	?	?	?	n/a
Acceptability	+	0	0	?	?	n/a
Transformation	++	++	++	+	++	n/a

2.5.2 Carbon tax interactions

We hypothesize that a carbon tax would make a positive contribution to both the effectiveness and cost-effectiveness of policy mixes based on the policies in Table 2.5, while potentially reducing political acceptability. The impacts on transformative signal are unclear. Addressing each criterion in turn:

- **Effectiveness:** Carbon taxes have often been found to be effective in reducing GHG emissions in general (e.g., Sterner, 2007), and can complement more technology-specific policies because the tax addresses all three "legs" of the mitigation stool. Specifically, the five other policies in Table 5 address either low-carbon fuels or improved vehicle efficiency, while a carbon tax can potentially induce some amount of VKT reduction (Fox et al, 2017). The presence of a carbon tax can also avoid some of the rebound effects that can be induced by efficiency-inducing policies or low-carbon fuels based policies that reduce the cost of travel (Small, 2012).

- **Cost-effectiveness:** US-based welfare analyses also suggest that the addition of a carbon price can improve the cost-effectiveness of a policy mix that includes more technology-specific regulations (Fox et al., 2017; Small, 2012; Klier and Linn, 2010).
- **Political acceptability:** it seems clear that addition of a carbon tax will reduce the political acceptability of a policy mix in most cases (Eriksson et al, 2008). A survey of Canadian citizens finds that the carbon tax is the most likely climate policy to be opposed, with the lowest rate of acceptance (Rhodes et al, 2017). Similarly, a UK-based study finds that industry tends to oppose carbon pricing (Bristow et al, 2010). Some researchers indicate that the acceptability of a policy is connected to the perceived distributive impacts of the policy (Jaensirisak et al, 2005; Sterner, 2012), especially if lower-income household face more burden (e.g., Agostini an Jimenez, 2015 in Chile; Mathur and Morris, 2014 in USA; Callan et al, 2009 in Ireland). That said, equity impacts and perceived acceptability can be impacted by the design of the carbon tax, especially the use of revenue recycling ((Bento et al., 2009; Stanley and Hensher, 2017; Callan et al, 2009; Eliasson and Mattson, 2006; Sterner, 2010; Levinston, 2010; Chiroleu-Assouline and Fodha, 2014). Hence, a carefully designed carbon tax could potentially reduce political opposition to some degree.
- **Transformative signal:** Less is known about how a carbon tax may impact the transformative signal of a policy mix. Carbon taxes are technology neutral by design and hence do little to send a clear transformative signal towards a particular direction of transition (Azar and Sanden, 2011), such as driving more investment into electric versus hydrogen-based technology. Carbon taxes also do little to address other market failures that may exist, such as

underinvestment due to R&D spillovers (Lehmann, 2012). On the other hand, the carbon tax might send a stronger signal to an otherwise weak or short-term policy, such as ZEV charger deployment or 2-years of a purchase subsidy. However, we are unsure of the net direction of impact to a policy mix, and identify this as an area needing more research.

2.5.3 ZEV purchase incentive interactions

We hypothesize that ZEV purchase incentives can improve the effectiveness, political acceptability and transformative signal of a policy mix, while the implications for cost-effectiveness are not clear. Addressing each criterion:

- **Effectiveness:** Numerous studies in North America and Europe indicate that a ZEV purchase subsidy will increase ZEV sales, even when controlling for most other policies (Jenn et al, 2013; Jenn et al, 2018; Lutsey et al, 2015; Tietge et al, 2016; Mersky et al, 2016; Munzel et al., 2019). Given the potential for substantial well-to-wheels GHG reductions from ZEVs in Canada in the short and long-run (Kamiya et al., 2019), induced ZEV sales should contribute to GHG mitigation. However, one study indicates that the interaction between a subsidy and ZEV sales mandate is unclear – as the subsidy might just offset some of the intra-firm cross-price subsidisation that automakers might perform to comply with the ZEV mandate (Axsen and Wolinetz, 2018). We flag this particular interaction as an unknown that needs future research.
- **Cost-effectiveness:** incentives by their very nature add to the direct government costs of the policy. Thus, they may reduce the cost-effectiveness of some policy mixes, especially relative to a carbon tax, due to inevitable free-ridership and the need for high government expenditure (Jaccard et al, 2003; Morrow et al, 2010; Axsen and Wolinetz, 2018). Though, certain design features can potentially improve the efficiency of a subsidy program (DeShazo et al., 2017). We hypothesize that a subsidy might improve the efficiency of a charger deployment program (which might not have much effect on its own), and are unsure of efficiency interactions with the three regulations.

- **Political acceptability:** because subsidies are often supported by politicians, citizens, and industry alike (Eriksson et al, 2008; Rhodes et al., 2017), we anticipate that they would improve the acceptability of nearly any policy mix. Though, free rider ship concerns may affect the acceptability of purchase incentives among some stakeholders (Jaccard et al, 2003; Bakker and Trip, 2013), including perceptions of undue benefits to higher income households (Plotz et al, 2014; DeShazo et al., 2017). Though, DeShazo et al. (2017) outline a number of design principles that can improve the equity impacts of a ZEV subsidy program – which might also improve political acceptability.
- **Transformative signal:** incentives can easily be directed towards a specific technology (e.g. ZEVs) and hence are likely to contribute to picking technology winners and sending a transformative signal, as has been found in Norway (Bjerkan et al, 2016). However, it needs to be kept in mind that the premature removal of incentives could negatively affect their ability to send a long-term transformative signal (Hardman et al, 2017; Melton et al., 2017).

2.5.4 Charging deployment interactions

We hypothesize that charger deployment can support the political acceptability and transformative signal of a policy mix, while likely reducing cost-effectiveness, and having unclear impacts on GHG mitigation.

- **Effectiveness:** Some studies found that charger rollout can help to increase electric vehicle sales (Lin and Greene, 2011; Greene et al, 2014; Mersky et al, 2016), while others find little effect (Bailey et al., 2015). A comprehensive review concludes that literature is not sufficiently mature to draw any conclusions about the role of infrastructure to support the uptake of PEVs (Hardman et al, 2018).
- **Cost-effectiveness:** Due to the lack of effectiveness, and high costs of deployment, we hypothesize that charger deployment would reduce the cost-effectiveness of most policy mixes (Schroeder and Traber, 2012; Peterson and Michalek, 2013). We acknowledge that some are more

optimistic about the cost-effectiveness of fast charging infrastructure (Funke et al., 2019).

- **Political acceptability**: charger deployment typically enjoys high political support (Sørensen et al, 2014). In particular, rollout of chargers could be seen as supporting automakers (and fuel providers) in policy compliance and thus should positively contribute to the acceptability of regulations.
- **Transformative signal:** charger deployment is technology-specific and visible, and can help to build confidence among stakeholders about the direction of technology change. But here again, we are unaware of any modelling studies that attempt to quantify the impact that charging infrastructure may have on political acceptability and transformative signalling.

2.5.5 Low-carbon fuel standard (LCFS) interactions

We hypothesize that an LCFS can support the effectiveness of most policy mixes (perhaps aside from one with a ZEV mandate), as well as improve political acceptability and transformative signal. Impacts on cost-effectiveness are less clear.

- **Effectiveness:** While some contrary views remain (e.g. Holland et al, 2009; Creutzig et al, 2011; Plevin et al, 2017), a number of studies demonstrate that LCFS can be effective in achieving GHG mitigation goals when in combination with other policies (Yeh and Sperling, 2010; Huang et al, 2013; Whistance et al, 2017; Lepitzki and Axsen, 2018). The LCFS can lead to additional GHG emissions abatement, mainly by incentivizing the development and usage of lower-carbon forms of electricity, as well as other lower-carbon fuels for use in plug-in hybrids, hybrids and conventional vehicles. Though, in a region that already has nearly zero-emissions electricity (such as British Columbia), an LCFS may have little additive effects in the light-duty vehicles sector in the presence of a ZEV mandate (Leptizki and Axsen, 2018). However, the incremental effect of adding a LCFS can potentially be higher in regions that have fossil-based electricity sources.
- **Cost-effective:** When examined in isolation, the LCFS is often found to be a costly (less cost-effective) policy (Holland et al, 2009; Creutzig et al,

2011; Chen et al, 2014). However, as Lade and Lin Lawell (2015) point out, the interaction of low carbon fuel standards with other carbon policies (particularly on cost-efficiency criterion) is a very important omission in transport policy literature. While some recent studies (e.g. Huang et al, 2013; Whistance et al, 2017) have started to address this gap, examining interactions between California's LCFS with the national renewable fuel standards in the US, interactions with other transport policies remain under examined.

- **Political acceptability:** the LCFS has been found to be popular among Canadian and Spanish citizens (Loureiro et al., 2013; Rhodes et al., 2015). There is of course some opposition in industry, namely incumbent fossil fuel providers – while providers of low carbon-fuels (electric utilities, biofuel companies) stand to benefit.
- **Transformative signal:** as seen in California, an LCFS tends to trigger additional stakeholders to invest in a low-carbon transition, including fuel providers and electric utilities (Sperling and Eggert, 2014). For example, the LCFS has more recently led to fuel suppliers contributing to purchase incentives for plug-in electric vehicles (UCS, 2019). However, it is especially challenging to quantify such impacts.

2.5.6 Vehicle emissions standard (VES) interactions

We hypothesize that the addition of a VES can provide an additive improvement to GHG mitigation and transformative signal to some policies, while other interactions are more uncertain.

- **Effectiveness:** when the requirements are stringent, a VES has generally been found to be effective (Small and van Dander, 2007), particularly in reducing the carbon intensity of vehicles, even when counting for rebound effect on vehicle usage (Linn, 2013). Though, it is particularly unclear how policy effectiveness will interact with other regulations. For example, in a US based modelling study, fuel economy standards combined with taxes and tax credits achieved lower GHG reductions compared to taxes alone, potentially due to unintended interactions between tax credits and fuel economy standards (Morrow et al, 2010). Whistance and Thomson

(2014), suggest that fuel economy standards when added to alternative fuel production incentives could lead to a decrease in gasoline demand, potentially reducing emissions. Small (2012) found that the combination of fuel tax and vehicle emission standards, reduced more GHG emissions than either policy alone. On the other hand, Jenn et al (2016, 2019a) find that VES combined with alternative fuel vehicle production incentives lead to increased GHG emissions in the near-term compared to either policy alone. Thus, even though vehicle emissions standards policy is one of the most studied regulations in transport literature, results are quite variable regarding GHG interaction effects.

- **Cost-effectiveness:** Some studies suggest that a VES adds low or moderate amount of costs when added to other policies (Small, 2012; Karplus et al, 2013; Whistance and Thompson, 2014; Jenn et al, 2019b). For example, Karplus et al. (2013) find that when combined with a cap-and-trade policy, fuel economy standards increase the cost of meeting the GHG emissions constraint by forcing expensive reductions in passenger vehicle gasoline use, displacing more cost-effective abatement opportunities. Small (2012) find that fuel economy standards moderately add to policy costs when added to taxes. Though, Small also adds that the costs of the combination (fuel economy standards and taxes) is less than the sum of individual policy costs, indicating complementarity between the two policies (Small, 2012). We hypothesize that a VES could have a small negative effect on the cost-effectiveness criterion, though we acknowledge that there continues to be debate on the estimated welfare impacts of a VES (Whistance and Thompson, 2014; Small, 2012).
- **Political acceptability:** a VES tends to be supported by Canadian citizens (Rhodes et al, 2017), and hence the addition of the VES to the policy mix might have a similar impact on political acceptability as the LCFS. While automakers tend to oppose such a policy, its acceptability also benefits from a long history (and presence in both Canada and the US, as well as many other countries internationally), which can improve perceived credibility. That said, some economic research indicates that a VES can have more negative impacts on low-income households (Davis and Kittel,

2019; Jacobsen, 2013), and on automakers profits (Jacobsen, 2013) – all of which could translate to reduced political acceptability in some circumstances.

- **Transformative signal:** Although a VES policy has effectively channelled incremental improvements into fuel economy (Plotkin, 2009), the transformational ability of the policy is heavily dependent on its stringency. For example, the present VES stringency levels in Canada and the US do not seem to be enough to induce larger transformative change, i.e. towards widespread deployment of ZEVs (Melton et al, 2017). At the same time, some overlap between supply side policies (e.g. ZEV mandate and VES) may only increase the transformative signal to automakers as it provides even more reward for the development and sale of ZEVs.

2.5.7 Zero-emissions vehicle (ZEV) sales mandate

The ZEV mandate and its interactions with other policies has remained relatively under-examined in transport literature (Jenn et al, 2019b; Greene and Ji, 2016). From the available information, we hypothesize that a ZEV mandate will increase the effectiveness of most policies, as well as transformative signal. Much less is known about cost-effectiveness and public acceptability.

- **Effectiveness:** ZEV mandates have been found to be effective in various jurisdictions (Greene et al, 2014; Lutsey et al, 2015; Sykes and Axsen, 2017; Ou et al, 2018). However, some recent US based studies (e.g. Goulder et al, 2012; Jenn et al, 2017; 2019a) suggest that the addition of the ZEV mandate to a VES could potentially increase GHG emissions in the US (compared to the VES alone). Such an interaction is likely due to the present design of the VES in the US (which is similar to the Canadian version), which arguably provides too many extra credits for ZEV sales (at least relative to their actual GHG mitigation potential). Presumably a change in VES design could substantially improve such interactions. In any case, this dichotomy of results across studies again brings forth how important the design of policies and their potential interactions can be - in certain cases, mitigating the effects of two individually strong policies.

- **Cost-effectiveness:** Very few studies quantitatively examine the cost-effectiveness of interactions of the ZEV mandate with other policies. Two recent notable studies (Jenn et al, 2019b for US; and Ou et al, 2018 for China) find interactions between a ZEV mandate and a VES policy can increase automaker costs. For example, Jenn et al (2019b) find that the costs to automakers increases from $1,600 per vehicle under VES standards alone to $2,000 per vehicle under a combined VES and ZEV regulation scenario. However, these two studies also did not consider the impact of policy interactions on consumer utility, or social welfare more broadly.
- **Political acceptability:** ZEV mandates have met with opposition from the auto industry over time (Collantes and Sperling, 2008; Wesseling, et al., 2015), though citizens tend to support supply-focused regulations (Rhodes et al, 2017). We hypothesize that the ZEV mandate would be more acceptable than a carbon tax alone, but that it is not clear if it improves the acceptability of other policy mixes.
- **Transformative signaling:** In terms of transformative signaling, the ZEV mandate policy can be hypothesized to send a clear, strong, and long-term signal (e.g. if the required percentage increases over time to ambitious levels) in favour of alternative fuel vehicles by clearly addressing some supply side barriers, such as lack of technological progress (Greene and Ji, 2016). Fox et al. (2017) in particular find that a more technology-specific ZEV mandate (requiring electric vehicle sales, rather than allowing competition with hydrogen and biofuels), can trigger an earlier technology breakthrough (which also improves long-run cost-effectiveness).

2.6. Discussion and conclusions

In this paper, we identify gaps in transport literature regarding policy mixes, particularly for the case of climate policy for light-duty vehicles. In Canada, the US and several other countries, this sector is typically impacted by a number of different policies, such as vehicle emissions standards, low-carbon fuel standards, zero-emissions vehicle standards, as well as subsidies, non-financial incentives (such as high-occupancy vehicle lane access) and infrastructure deployment. Yet there is little sophisticated discussion in transportation literature about why such policies are mixed together, and what combinations would be "better" for various societal goals – especially for climate policy with light-duty vehicles.

One basic goal of this paper is to bring the concept of policy mixes and policy interactions more to the forefront of transport policy work, especially for climate policies affecting the light-duty vehicle sector. Further, we want to stimulate reflection on policy interactions beyond just GHG effectiveness, and cost-effectiveness, but also impacts on political acceptability and processes of innovation and societal transformation. We believe this acknowledgment of interactions and their complexity can improve the work of transportation researchers, especially quantitative policy modelers, as well as policymakers seeking to "patch" together policy mixes that not only help with long-term GHG mitigation goals, but also improve the durability and credibility of the policy mix – including the likelihood that it will be implemented in the first place, and stay implemented in the long run. Finally, we believe this exercise helps to identify important research gaps that should help to direct and prioritize future research efforts.

Next, we summarize our review, framework and illustration, followed by a more explicit discussion of research gaps.

2.6.1 Summary

Consulting the broader energy and policy literature, we identify several general rationales for policy mixes:

(i) the "three leg" perspective that different policies should address different sub-sectors of GHG mitigation (e.g., vehicles, fuels, and travel demand), recommended by studies such as Schafer (2005), Sperling and Eggert (2014) and Creutzig et al (2011);

(ii) the "market failure" perspective that a different policy is needed to correct each market failure (e.g., negative externalities and R&D spillover effects), recommended by studies such as Bennear and Stavins (2007), Lehmann (2012) and Twomey (2012) among others;

(iii) the "political process" perspective that considers the reality of the present policymaking context, including the political acceptability of policy instruments, recommended by studies such as del Rio (2014), Howlett and Rayner (2013) and Kern et al (2017); and

(iv) the "systems" perspective that policy needs to send signals to channel innovation and break any lock-in to incumbent technologies and practices, recommended by studies such as Smith (2000), Foxon and Pearson (2008), Weber and Rohracher (2012) and Rogge and Reichardt (2016).

Building from the reviewed literature and perspective, we propose a simple qualitative framework to help to explore and to generate hypotheses regarding interactions between various policies. We consider four broad criteria for policy interactions, considering if the added policy can provide an additive effect in terms of: 1) effectiveness at GHG mitigation, 2) cost-effectiveness ($ per tonne/CO_2e abated), 3) political acceptability, among citizens and stakeholders, and 4) transformative signal, that is, providing a clear stimulus for various stakeholders to invest and contribute to the transition to one or more low-carbon pathway.

We illustrate this framework using the case of six climate policies in British Columbia, Canada, which apply to light-duty vehicles: a carbon tax, ZEV purchase incentives, charging infrastructure rollout, an LCFS, a VES and a ZEV sales mandate. Based on literature, empirical evidence, and logic, we discuss hypotheses for how each pairing of policies (adding one to the other) could produce an additive, negative or neutral impact on each of our four criteria. While the direction of interactions seems clear for some policy interactions on some criteria, we identify a high degree of ambiguity for a large number of policy interactions – such that we do not feel comfortable hypothesizing a given direction of interaction. In examining our hypotheses for each policy type, we also identify several hypotheses of what strengths (and weaknesses) each policy could bring to a policy mix:

- A carbon tax is likely to improve the GHG mitigation and cost-effectiveness of a light-duty vehicle policy mix, while reducing its political acceptability.
- A ZEV purchase subsidy is likely to improve GHG mitigation and political acceptability, as well as transformative signal if implemented for the long-term.
- Charger deployment is likely to improve political acceptability, as well as transformative signal.

- An LCFS is likely to improve GHG mitigation (though maybe not with a ZEV mandate present), as well as political acceptability (among citizens) and transformative signal.
- A VES is likely to improve GHG mitigation (depending on design), and potentially improve political acceptability and transformative signal.
- A ZEV mandate is likely to improve GHG mitigation (though in some cases, perhaps not with a VES present in the near-term), while improving the transformational signal.

Even these hypotheses indicate only the expected direction of interaction, where empirical analysis and quantitative modeling would be required to confirm the validity of these hypotheses and estimate the magnitude of effects for particular policy mixes, at particular stringencies, in a particular region. In our application we also identify numerous interactions that are particularly uncertain, such that we did not feel comfortable guessing the direction of effect (if any), including:

- Would a carbon price improve the transformative signal when added to another policy?
- Would a ZEV purchase subsidy produce an additive improvement in GHG mitigation or cost-effectiveness, when added to a regulation (LCFS, VES or ZEV mandate)?
- Would charger rollout improve GHG mitigation?
- How would any of the three regulations (LCFS, VES or ZEV mandate) impact the cost-effectiveness of a policy mix?
- How would a ZEV mandate impact the political acceptability of a policy mix?

Such uncertainties may stem from lack of existing studies, unavailability of data, or difficulty in modelling complex real-world dynamics. This illustrative exercise can thus help to qualitatively identify policy pairs that require more detailed examination and thus inform priorities for future research, including data collection, empirical analysis and quantitative policy modelling exercises.

Our work is not without limitations. We acknowledge that the absence of empirical data on policy interactions may limit the validity of our assertions. Another limitation of this study is that we potentially miss out several criteria that may be important from a policymaker’s perspective, such as equity which we do not explicitly consider as a separate criterion. Finally, our present focus is on GHG emissions reduction for light-duty vehicles and we thus miss out other transport policy relevant goals such as improvements to traffic congestion, safety, urban livability and local air pollutant reduction.

2.6.2 Research gaps and research agenda

Aside from the more specific gaps on interaction knowledge noted above, we also identify several critical research gaps, including the need: (i) to further improve GHG research by quantitatively examining the effectiveness and cost-effectiveness of interactions between multiple policies, (ii) to include interdisciplinary and multi-criteria approaches to examine policy mix interactions and (iii) to examine different types of interactions (beyond just complementarity) between policies.

First, while climate and GHG policy focussed transport literature has started to move in the direction of analysing interactions between multiple policies using quantitative modelling (e.g. Small, 2012; Greene et al, 2014; Jenn et al, 2016; Lepitzki and Axsen, 2018; Axsen and Wolinetz, 2018; Ou et al, 2018; Jenn et al, 2019b), more work is needed in this area. In particular, while policies such as carbon taxes and vehicle emissions standards have received comparatively more focus in literature, further research may be directed towards modelling interactions of policies such as the ZEV mandate and charging deployment with other policies on effectiveness and cost-effectiveness criteria (including effect of consumers), which has rarely been examined. To conduct such analyses, models need to be equipped to realistically simulate multiple policies – including consumer and industry behaviour. Also, to be able to examine development of policy interactions over time, models need to be able to simulate long-run dynamics in behaviour and technology. Few transport modelling studies consider long time horizons or simulate utility, profit or government expenditure impacts.

Second, another potential priority for future climate policy mix research for light-duty vehicle transport is to move beyond just effectiveness and cost-effectiveness and toward interdisciplinary and multi-criteria evaluation of policy mixes. Thus, future transport research may also need to explore newer methods to conduct a holistic interdisciplinary multi criteria analysis. To quantify the effect of criteria such as public acceptability, methods could be borrowed from other disciplines, such as representative surveys or stakeholder interviews. Methods such as the Analytic Hierarchy Process (AHP) from Operations Research could be used for solving a multi-criteria decision-making problem. Turcksin et al (2011) provide one notable example of how AHP could be used for integrated multi-criteria decision making for transport policy in Belgium. Additionally, there may be scope for making methodological improvements to existing models. For example, most quantitative models used in climate policy analysis are partial equilibrium models (e.g., in studies by Jenn et al, 2019b, Axsen and Wolinetz, 2018; Small, 2012). Some of the system wide effects (such as transformative signalling) may be analysed by combining these partial equilibrium models with a system dynamics model (e.g., one such attempt is by Kieckhafer et al, 2017), or general equilibrium model. Similarly, metrics such as R&D investment may be used to operationalise the transformative signalling criterion. However, challenges are likely to remain as existing data is sparse, and due to difficulty in modelling complex real-world policy mix dynamics. Climate policy for light-duty transport may also benefit from considering an even more integrated approach where multiple goals are simultaneously pursued (e.g. congestion reduction and other co-benefits beyond just the primary goal of GHG emissions reduction).

Third, policies may interact in a variety of ways and examining various types of interactions may throw additional light on the potential relation between two or multiple policies (Flanagan et al, 2011; May et al, 2006; Oikonomou and Jepma, 2008). Various types of interactions are recommended in literature:e.g. complementarity (Sykes and Axsen, 2017), synergy (May et al, 2006), policy sensitivity (Greenblatt, 2015) and policy robustness (May and Roberts, 1995) to name a few. Complementarity exists when the use of two policies gives greater total benefits than the use of either policy alone. Synergy, a sub-type of complementarity, occurs when the simultaneous use of two or more policies gives a greater benefit than the sum of the benefits of using either one of them alone (May et al, 2006). Policy sensitivity refers to the incremental contribution of each policy (Greenblatt, 2015), while robustness indicates how robust a policy benefit is to exogenous factors such as technology costs and resource prices (May and Roberts, 1995). See Oikonomou and Jepma (2008) and Howlett and Rayner (2013) for a discussion on other possible interactions. While transport literature so far has almost exclusively analysed interactions based on complementarity (or not) between policies, consideration of other types of interactions may lead to a richer discussion of policy mixes, providing more useful insights about the relationships between policies.

Chapter 3. Simulating automakers' response to zero emissions vehicle regulation[4]

Abstract

Little research explores automaker response to supply-focused regulation in the long-run, such as zero-emissions vehicle (ZEV) mandates. To that end, we develop and apply the AUtomaker-consumer Model (AUM), which simulates interactions between behaviorally-realistic consumers and profit maximizing automakers from 2020 to 2030. AUM endogenously represents multi-year foresight for automakers, including decisions about: (i) increasing ZEV model variety, (ii) intra-firm cross-price subsidies, and (iii) investing in R&D to reduce future ZEV costs. Under both optimistic and pessimistic conditions, automakers are simulated to fully or mostly comply with a 2030 requirement of 30% ZEV sales (rather than pay a penalty). Of the three compliance mechanisms, intra-firm cross-price subsidization dominates. The policy could reduce automaker profit by 7% to 44% in 2030 (relative to the baseline in the same year), mostly due to reduced vehicle sales in total, though overall profits still grow year-on-year from 2020. We identify key uncertainties in these results.

[4] This paper was published as Bhardwaj, C., Axsen, J. and McCollum, D., 2021. Simulating automakers' response to zero emissions vehicle regulation. Transportation Research Part D: Transport and Environment, 94, p.102789. Drs. Axsen, and McCollum, helped in the writing (review and editing) of this paper, as well as guided me during the conceptual design stage.

3.1. Introduction

Technology adoption models are commonly used for transport climate policy analysis. Although there are numerous climate policies for light-duty vehicles that influence automakers and consumers, there has been little attempt to endogenously and simultaneously model the decisions of both over the long-term (10 years or more). In this paper, we develop a new technology adoption model that attempts to do so, and demonstrate it using the case of a Zero-Emissions Vehicle (ZEV) sales mandate in Canada. We note that the population of Canada is of similar size to California, the region that first enacted the ZEV mandate in 1990. In this study, we focus on plug-in hybrid vehicles (PHEVs) and battery-electric vehicles (BEVs), collectively plug-in electric vehicles (PEVs), which dominate the ZEV market in most regions.

Supply-focused climate policies are common for light-duty vehicles in much of North America and Europe, and increasingly other countries like China – including fuel economy standards, ZEV sales mandates, and low-carbon fuel standards. Such policies are often recommended as part of climate change mitigation efforts (McCollum and Yang, 2009; Creutzig et al., 2011; Sperling and Eggert, 2014; Melton et al., 2017; Axsen et al, 2020). Policy success is inevitably linked to automakers' strategic responses to these policies and how these strategies interact with consumer behaviour over the long term (Greene and Ji, 2016). As noted, however, this remains an under-researched area in literature (Jenn et al., 2018). Technology adoption models for PEVs have typically focussed either only on consumers or automakers but rarely both. There is still great uncertainty in how automakers may respond to such policies over the long-term, and how such policies might ultimately impact PEV market share and automaker profits

We attempt to address this gap by developing AUM (or AUtomaker-consumer Model) a technology adoption model, with an explicit, endogenous representation of both consumers and an automaker agent (the latter being at the aggregate domestic level as a single firm). that endogenously simulates automaker-consumer decision-making and behaviour to examine the effects of a ZEV mandate (and other supply-side policies) to estimate the uptake of PEVs in new vehicle market share. To demonstrate AUM, in this study our overall objective is to simulate the effect of a ZEV mandate requiring 30% ZEV sales by 2030, over the decade from 2020 to

2030. To do so, AUM endogenously simulates automaker response to policy, namely decisions about markup (profits per vehicle) and policy compliance mechanisms (investing in Research and Development or R&D, increasing model variety and price cross-subsidization).

One intention of this research is to examine which of these mechanisms an automaker may utilize to comply (or not comply) with a ZEV mandate in a region that represents only a small fraction of global vehicles sales. That is, with a ZEV mandate in a market the size of Canada or California, does the automaker comply with the policy, and if so, how? Do automakers invest substantially more in general R&D and increasing model variety (a global effort), or by changing prices in that one market (a local effort)? Our analysis also assesses overall policy impacts on automaker profits and consumer welfare (the latter is summarized in the SI document).

The paper is organized as follows as follows. Section 3.2 reviews the literature on technology adoption models to identify gaps. Section 3.3 describes the model developed to conduct this analysis. Section 3.4 presents the results. Section 3.5 summarizes and concludes. A Supplementary Information (SI) document includes the detailed framework for our literature review, our summary of model validation, justification for our uncertainty analysis, and a part of our results on consumer welfare. In addition, it contains model results discussing the ZEV mandate policy impacts on consumer welfare, and the effect of foresight on automaker decisions.

3.2. Literature review: ZEV adoption models

Several studies review existing PEV adoption models and make recommendations on the attributes that a good model should contain (Al-Alawi and Bradley, 2013; Wolinetz and Axsen, 2017). To summarize and compare different modelling approaches, we use and extend Wolinetz and Axsen's (2017) recommendations into three broad categories of attributes:

- Realistic consumer behaviour: representation of consumers valuing non-financial factors (Choo and Mokhtarian, 2004; Horne et al, 2005; Heffner et al., 2007; McCollum et al, 2017), heterogeneity among consumers (Bunch et al, 2015; Higgins et al., 2017), use of empirically-informed parameters (Al-Alawi and Bradley, 2013), and dynamics in consumer parameters over time (Axsen, et al. 2009; Axsen and Kurani 2013).

- Explicit supply-side features: endogenous automaker decision-making (Al-Alawi and Bradley, 2013), representation of vehicle model variety and availability (Wolinetz and Axsen, 2017), forward-looking automakers (Klier and Linn, 2010), technological change (learning by doing and/or learning by searching) (Sterman et al., 2015), and multiple policy compliance mechanisms (Anderson and Sallee, 2011; Wessling et al.,2014; Mazur et al., 2015; Whitefoot et al., 2017).
- Endogenous policy response: of consumers and automakers to both supply-focused policies (such ZEV sales mandate, vehicle emissions standard), and to demand-focused policies (such as purchase incentives and charging infrastructure (Greene et al., 2014; Greene and Ji, 2016; Sykes and Axsen, 2017).

We discuss these evaluation criteria in more detail in the Supplementary Information document. Using this framework, we summarize the reviewed literature into three categories of models: supply-focused models, consumer-focused models, and integrated models (Table 3.1).

First, supply-focused models represent automaker decision making endogenously and often in great detail with multiple automakers, vehicle technology types, and vehicle classes. Such models are commonly used for evaluating automaker compliance with supply-focused policies, such as altering vehicle attributes such as acceleration, vehicle footprint, or drivetrain changes to comply with a vehicle emissions standard or CAFE (Michalek et al., 2004; Whitefoot et al., 2017). Some models use an optimization approach to represent automaker action, where system costs are minimized, subject to policies which are treated as hard constraints rather than as part of endogenous decision making. Examples include the COMET model used by Jenn et al. (2018). Others use a decision tree model of automaker decision making to predict which technologies each automaker might use to comply with regulations (e.g. VOLPE model in Al-Alawi and Bradley, 2014). As Xie and Lin (2017) point out, most of these models focus on technology feasibility and cost-effectiveness, often completely ignoring the consumer perspective.

Table 3.1: List of representative ZEV market share modelling studies

Model category	Consumer-focused		Supply-focused		Integrated		
Authors	Plotz et al. (2014)	Xie and Lin (2017)	Al-Alawi and Bradley (2014)	Jenn et al. (2018)	Sen et al. (2017)	Thiess et al (2016)	Current study
Model name/ Modelling approach	ALADIN Discrete choice	MA3T Discrete choice	VOLPE	COMET	EVRemp (Agent-based)	System dynamics	AUM
Consumer-side features (Behavioural realism)							
Empirically -informed parameters.	√					√	√
Consumer heterogeneity	√	√			√		√
Non-financial factors	√	√			√	√	√
Dynamic preferences	√	√				√	√
Supply-side features							
Model variety	√	√	√	√			√
Endogenous automaker decision-making			√	√	√	√	√
Multiple compliance mechanisms							√
Learning by doing		√				√	√
Learning by searching						√	√
Forward-looking automaker (foresight)							√
Endogenous Policy response							
Consumer-focused policies (e.g., incentives, chargers)	√	√					√
Supply-focused standards (e.g., sales mandate)							√

Note: The tick signs represent the features included in the model

However, there exist studies among supply- focused literature that do consider some representation of consumers. Few such exceptions include work by Whitefoot et al. (2017) and Michalek et al (2004). Both these studies account for consumer preferences using discrete choice logit modelling. However, these studies are more focused on examining the effect of the policy on vehicle design. As a result, these studies contain a less detailed representation of the consumer side. For example, Michalek et al (2004) assume one representative consumer and also do not include the effect of charging infrastructure, model variety, or other non-financial factors. Moreover, these studies typically focus on the short term (one-year foresight) and do not represent automakers that can plan ahead in a forward-looking manner (Michalek et al., 2004; Al-Alawi and Bradley, 2014; Whitefoot et al., 2017).

Second, consumer-focused models represent a higher degree of behavioural realism, typically using a utility function and discrete choice models to simulate vehicle market share (Al-Alawi and Bardley, 2013). Notable examples include the MA3T model in Xie and Lin (2017), LAVE-Trans in National Research Council (2013), and ALADIN in Plotz et al. (2015). Discrete choice models, such as in Xie and Lin (2017), can represent consumer heterogeneity using multiple market segments and include consumer valuation of various non-monetary factors (such as risk, refuelling infrastructure, and range anxiety). One important critique of these discrete choice models is that they tend to focus less on the representation of the supply-side. While some supply-side features such as model availability have been included in some models (e.g. Xie and Lin, 2017; Plotz et al., 2015; Wolinetz and Axsen, 2017), studies in this category do not endogenously model automaker behaviour, limiting their usability in examining the automaker compliance decisions, or the effects supply-focused policy more generally.

Our third category is integrated models, which aim to represent both the supply and demand side endogenously. There are relatively few examples of such attempts. A couple of studies use agent-based models (ABMs) to simulate the interactions between agents, such as a large number of individual consumers, as well as potentially other agents such as automakers and governments, each of which is governed by a set of rules, subject to constraints (Sullivan et al., 2009). A more recent ABM example is the EVRemp model used by Sen et al. (2017). ABMs are naturally predisposed to represent heterogeneity quite well. However, many ABM studies so far have lacked an empirical basis for input parameters and have neglected dynamic learning by doing effects for technological change. Another set of studies has used system dynamics models, which are notable for representing endogenous feedback loops governing the evolution of the system over time (e.g. Thies et al., 2016; Walther et al., 2010). However, in existing system dynamics modelling literature, there is an absence of representation of consumer heterogeneity and endogenously determined automaker and consumer response to supply and consumer-focused policies.

In summary, each category of PEV technology adoption model has its strengths and weaknesses. While system dynamics models have made progress in depicting dynamic learning, agent-based models may be more suitable for representing heterogeneity across actors. While optimizing frameworks more closely describe supplier or automaker behaviour, a discrete choice logit framework more accurately captures consumer behaviour. In this study, we borrow components from different models to develop an integrated, policy-relevant light-duty vehicle supply and adoption model, which (i) represents consumer behaviour (heterogeneity and non-financial factors), (ii) models supply-side policies (using a representation of forward-looking automaker behaviour), (iii) incorporates dynamic learning (learning by doing and learning by searching, including feedbacks), and (iv) uses empirical survey data to inform our model.

3.3. Method

AUM attempts to mimic the dynamics within the light-duty vehicle sector in Canada, treating the rest of world as exogenous. As depicted in Fig. 3.1, AUM combines a behaviourally realistic consumer component with a profit-maximizing automaker component to endogenously model consumer-automaker interactions and simulate plug-in electric vehicle (PEV) new market share up to 2030. The consumer component is a simplified representation of Canadian consumers and the automaker component is a simplified representation of the Canadian auto industry. The Canadian domestic automaker is treated endogenously, while external factors (e.g. vehicles produced outside Canada or economies of scale) are treated exogenously. The automaker (or vehicle supply) model and the consumer choice (demand side) model interact by passing data at each one-year timestep.

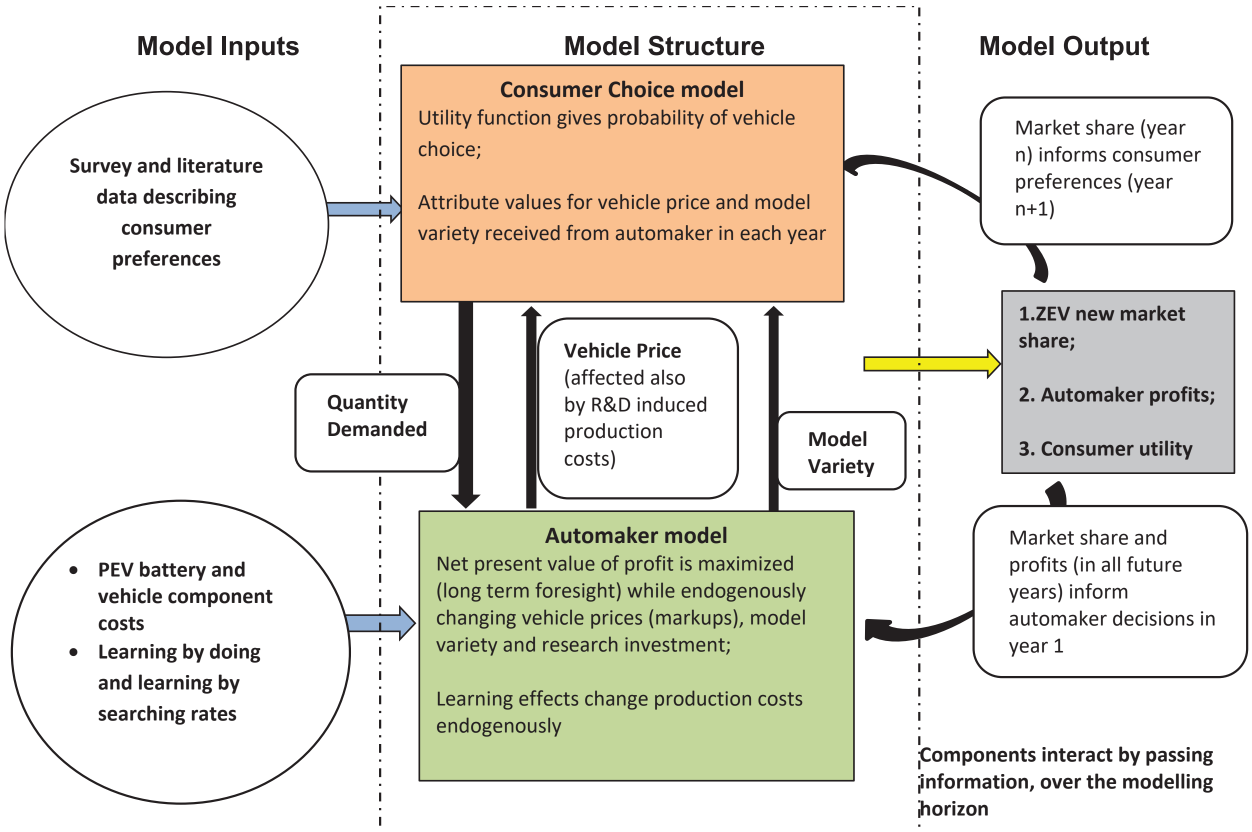

Fig. 3.1 Structure of the AUtomaker-consumer model (AUM)

AUM is dynamic, and the automaker and consumer components iterate to equilibrium over the entire foresight length chosen. The foresight can be any number from 1 to 10. Thus, if foresight is set to 1 year, the model will equilibrate in each one-year time step, over the modelling horizon. If foresight is five years, it equilibrates in each 5-year step and so on. As examples, the automaker model selects prices, R&D investment, and the number of vehicle models available, while in each year, consumers demand a certain quantity 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, which feed back into the model to affect the output for the following years. The model can thus be used to analyse the long-term effects of a variety of policies (in particular supply-focused policies) based on their impact on several outcome indicators, namely ZEV market share, automaker profits and consumer utility.

The rest of this section elaborate on the consumer choice model, the automaker model, and policy scenarios for this study. The Supplementary Information document contains further information on model validation and uncertainty analysis.

3.3.1 Demand-side: The consumer choice model

The consumer choice model simulates annual new light-duty vehicle sales over the modelled time horizon. Total vehicle sales are in turn affected by prices generated by the automaker model using own price elasticities of -0.3 to -1 are taken from Fouquet (2012) and Holmgren (2007), depicted in Table 3.3. In each year, consumers choose from the available options to satisfy the demand for new vehicles, generating annual light-duty vehicle market share. The model assumes that the new vehicle demand will grow at a default exogenous rate, but is responsive to vehicle prices and fuel costs. Thus, vehicle prices can change in response to policies such as the ZEV mandate, e.g. as in Fig 3.3. Similarly, fuel costs can vary under the effect of taxes or fuel economy standards). Using own-price elasticities (Table 3.3), the default exogenous demand growth is modified to give the resulting total vehicle demand. So, if the automaker increases vehicle price markup, they could potentially lose profits due to lost vehicle sales, caused by reduced demand in response to price elasticities. The resulting demand is assumed to be met by buying a vehicle from the available list. Another approach to model the same effect can be a buy/no-buy approach, where a buy/no-buy option is included as part of the nested discrete choice model. The LAVE-Trans model in NRC (2013) presents one neat of using this approach.

The consumer choice model is a nested discrete choice model, similar to that used by the LAVE-Trans model in NRC (2013). At the first level of the nest, a consumer chooses between different vehicle classes (compact, sedan, SUV, mini-truck) as shown in Fig. 3.2, using coefficients are informed by the LAVE –Trans model. Although it would have been more appropriate to use Canada-specific coefficients, we use US data from National Research Council (2013) as a simplifying assumption. Our ratio of coefficients across vehicle classes are similar to those found in a Canadian survey conducted by Higgins et al (2017). Where consumers generally prefer larger vehicles (SUVs and mini-trucks) over smaller vehicles (compacts and sedans). At the second level, the consumer chooses between different vehicle drivetrain technologies (conventional internal combustion engine vehicles or CVs, hybrid, PHEVs or BEVs) within each class. To link levels 1 and 2, and 2 and 3, we again use coefficients borrowed from the LAVE-Trans model. For PHEV and BEV drivetrains, the third level of the nested discrete choice hierarchy is a choice of vehicle electric-driving range. PHEVs can include electric ranges of 60, 100, and 120 km, and BEVs can include ranges of 100, 180, 240, 320, and 380 km.

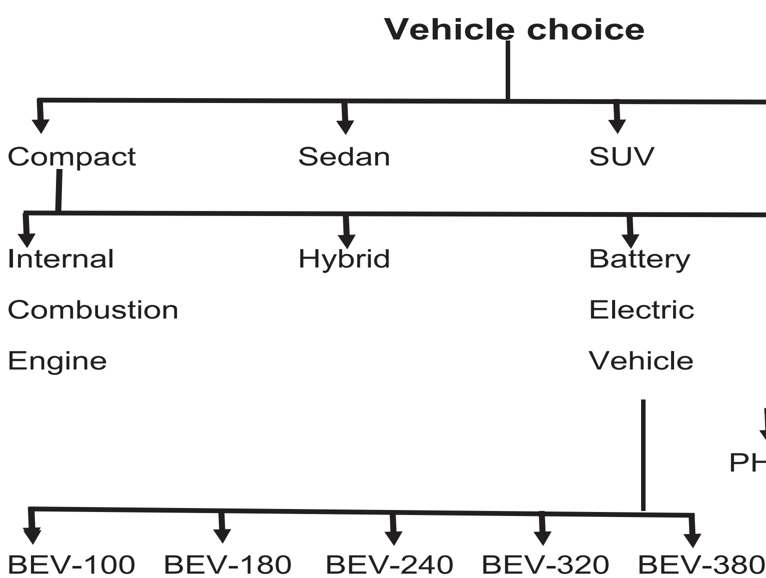

Fig. 3.2 Nested structure of the vehicle choice model. Level 1 is the top level with the vehicle class options (compact, sedan, SUV and mini-trucks). Level 2 represents the vehicle drivetrain technology options available in each vehicle class (CVs, hybrids, BEVs and PHEVs). Only one branch is shown here for the sake of compactness. Level 3 represents the range options available for BEVs and PHEVs. Only BEVs are shown here for the sake of clarity.

Consumers choose the vehicle technology which provides the highest utility, based on a utility function. In this respect, our model differs from some previous models (e.g. ALADIN in Gnann et al, 2015) that rely on a least total cost of ownership approach. The utility function draws largely from the LAVE-Trans model (National Research Council, 2013) as follows:

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

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).

1) Purchase price indicates the vehicle price (vehicle cost + markup added by automaker) as observed by consumers.
2) Fuel cost indicates the annual running costs of a vehicle.
3) Electric driving range indicates the number of kilometres a vehicle can run without needing recharging.
4) Recharging access (X_{CA})is the percentage of filling/recharging stations with electric charging, relative to gasoline stations (Hackbarth, and Madlener, 2016). Thus, a 50% access to recharging means that the number of PEV charging stations is 50% of the number of gasoline stations. Recharging access is assumed to change exogenously, typically under the influence of policies supporting infrastructure deployment. As also noted in the SI document, it is assumed to be 10% in 2020, and assumes values of 50% (pessimistic), 70% (base) and 90% (optimistic) in 2030.
5) Model variety (X_{MV}), expressed as natural logarithm of the percentage of PEV models relative to conventional vehicles, captures the idea that availability of models for battery electric and plug-in hybrid electric vehicles (n_{kt}) is limited, affecting consumers' purchase decisions. The value of model diversity is given by the logarithm of the ratio (n_{kt} /N_t, where N_t is the number of models of conventional vehicles) (Greene, 2001). The total number of models seen by Canadian consumers (n_{tk}) is the sum of models produced globally ($n_{Gtk;}$

exogenous) and models produced domestically (n_{ctk} ; endogenous). In 2020, about 28 models for PEVs exist in Canada, in comparison to about 300 for conventional vehicles. Thus, model variety for plug-in electric vehicles is ~ 10% relative to conventional vehicles.

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

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

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

The probability that technology *i* will be selected is the product of the probability of choosing a nest *j* (where *j* represents a nest at Level 1or 2 in Fig. 3.2) and the probability of choosing *i*, given that a choice will be made from the nest *j*: $P_{ij} = P_{i|j} * P_j$. The net change in consumer surplus (CS) in policy scenarios ('1') relative to the Baseline ('0') is given as:

$$\Delta CS = -\frac{1}{\beta_{PP}} \left[\ln\left(\sum_{i=1}^{n} e^{Ui^1}\right) - \ln\left(\sum_{i=1}^{n} e^{Ui^0}\right) \right] \qquad (2b)$$

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

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 (Axsen et al., 2015; Kormos et al., 2019), and in part from international literature (Brand et al., 2017; Dmitripoulos et al., 2013; Ferguson et al., 2018). Consumers' base year willingness to pay for the different attributes are listed in Table 3.2. The CPEVS included a three-part survey completed by a representative sample of 1754 new vehicle buying Canadian households in 2013 while the CZEVS 2017 survey is essentially an updated version of the 2013 survey. Both surveys contain responses to questions on PEV 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. These are “CV-oriented”, “HEV-oriented”, “ZEV-neutral”, “PHEV-oriented” and “PEV-enthusiasts” We combine these into three classes in our model, as described below in the paragraph on consumer heterogeneity.

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

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

Where the ASC_{ok} represents the value of the ASC parameter at time *t=0* for technology *k*; b = constant (as used in NRC, 2013).

While the data for all attributes in equation (1) for the first modelling year is exogenously specified, the data for each attribute for the remaining years are determined either exogenously (for fuel prices and charger availability, Table 3.3) or endogenously as inputs from the automaker model (Fig. 3.1). In particular, vehicle purchase price and model variety values are endogenously taken from the automaker model (Fig. 3.1). Model variety also has an exogenous component, to represent the global increase in the number of models (summarized in Table 3.3).

To represent heterogeneity in consumer preferences, we include three consumer segments: "ZEV Enthusiasts" (15% of new car buyers), "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. The CPEVS and CZEVS surveys that we draw from have five consumer segments. (Axsen et al, 2015; Kormos et al, 2019). For computational convenience, we combine these into three segments (Table 3.2):

1. “Enthusiasts”, correspond to “PEV-enthusiasts (13%)” in Kormos et al. (2019) and Axsen et al. (2015) and have a high positive valuation (negative risk aversion) for PEVs.

2. The “Resistors” segment, corresponding approximately to the

combination of "CV-oriented (23%)" and "HEV-oriented (21%)" classes in Kormos et al. (2019) and Axsen et al (2015), favour the conventional vehicles and have a significant negative valuation for electric vehicles.

Table 3.2: List of attributes and the corresponding estimated Willingness to pay values of their coefficients

Attribute	WTP (in CAD$)			Range in literature (in CAD$)	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 $1k 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)	Axsen et al. (2015), Kormos et al. (2019)
BEV	8000	-15000	-40000		
HEV	3000	-3000	- 5000		
ASC in 2030 (optimistic, pessimistic)					
PHEV	(2625,4375)	(-5250, - 8750)	(-15750, -26250)		
BEV	(3750,6250)	(-7875, -13125)	(-21000, -35000)		

HEV	(1575,2625)	(-1575, -2625)	(-2625, - 4375)

Table 3.3: Optimistic, Reference and Pessimistic values for key model parameters

Parameters	**Optimistic (in 2030)**	**Pessimistic (in 2030)**	**Source**
Model variety (relative to CVs) (10% in 2020)	90%	40%	Authors' judgement,
Recharging access (10% in 2020)	90%	50%	Authors' judgement
Gasoline price (70 CAD $/bbl in 2020)	92.1	177.9	National Energy Board (2019), US EIA (2020)
Battery costs (230 CAD $/kWh in 2020)	70	175	Nykvist et al. (2019)
Consumer price elasticity (2020-2030)	-0.3	-1	Fouquet (2012); Holmgren, (2007)
Automaker rate of learning (%) (2020-2030) **i.e. Learning by doing (LBD) and learning by searching (LBS) rates**	10	6	Weiss et al. (2012), Barreto and Kypreos (2004)
Automaker discount rate (%) (2020-2030)	8	15	Jagannathan et al. (2016)

Notes: Model variety represents the number of models of PEVs, as a percentage of the number of models of CVs. Recharging access represents the percentage of public refuelling/recharging stations relative to gasoline stations. Rate of learning indicates the percentage drop in vehicle production costs for every doubling of cumulative capacity or knowledge stock (equation 8).

3. "Mainstream" is a combination of "ZEV-neutral (21%)" and "PHEV-oriented (22%)" classes in Kormos et al. (2019) and Axsen et al (2015) into one segment. The "mainstream" segment represents a moderate bias against PHEVs. Although it seems conceptually reasonable to include the "HEV-oriented" consumers as part of the "mainstream" segment, we decided to combine it with resisters for two reasons: i) the cited Canadian studies show that HEV- oriented segment has similar PEV-related coefficients to the CV-oriented group, and ii), the size of the mainstream group would have been very large (76% of total consumer population), reducing the heterogeneity of the model. We believe it is worthwhile for future research to explore the specification of more or at different segments.

The coefficients in Table 3.2 are largely drawn from the two Canadian Surveys (Kormos et al., 2019; Axsen et al. 2015). For coefficients that we draw from other literature (sources noted in Table 3.2), which did not have identical number of consumer classes, we use our judgement to average them over these consumer segments.

3.3.2 Supply-side: The automaker model

The vehicle supply model is an optimization model that is designed to be a representation of the Canadian automaker industry at the aggregate level. As a simplifying assumption, we model the Canadian auto industry as if it were one automaker. While it would be interesting to simulate and observe the behaviour of a heterogeneous set of automakers, the present research paper is more concerned with overall ZEV adoption, and the overall impacts of a supply-focused climate regulation, in this case a ZEV mandate -- not impacts on specific automakers. We build on the optimization framework suggested by Michalek et al. (2004) (and later adapted by Zhang et al., 2011) and Kang et al. (2018).

We noted earlier that automakers are typically forward-looking and consider future costs and benefits in their present decisions, as would be reflected in net present profit value calculations. The number of years they are looking ahead determines their 'foresight'. The ZEV mandate policy is expected to have a long-term signalling effect in support of PEV uptake, as discussed in our recent qualitative analysis (Bhardwaj et al., 2020). Such long-term signalling may induce automakers to employ a longer foresight (than usual) for their production planning decisions. To examine the effect of foresight, we run the model under two cases- one with 10-year foresight (default) and a second with 5-year foresight (thus two 5-year periods from 2020 to 2030).

We also note in the literature review above that automakers may comply with a ZEV regulation in a variety of ways. The three compliance mechanisms we examine here are:

1. Increasing model variety: automakers may introduce new models in the modelled country to incentivize customers to buy more PEVs. We also

model a global exogenous increase in ZEV models (from developments in other countries).

2. Intra-firm cross-price subsidy schemes: automakers may adjust profit margins or markups for different vehicle technologies to shift/adjust the vehicle sales mix. In other words, to comply with a ZEV sales mandate, they charge a premium to reduce conventional vehicle sales and subsidize PEVs to increase their sale.
3. Investing in R&D to reduce vehicle production costs over time. AUM simulates that such investment can contribute to lower ZEV costs nationally over time, apart from the global exogenous decline in battery and other component costs.

Next, we describe how we mathematically represent these features.

The objective for the aggregate Canadian automaker is to maximize the net present value of profits over the foresight horizon, which we can set as any number of years within the modelling time horizon (in this case, from 2020 to 2030). The consideration of a long-term planning horizon (foresight) for the automakers is a novelty in this model with very few other studies conducting similar analyses (notably Kang et al., 2018). Most other previous studies modelling automakers consider a short term (1 year) foresight for the automaker (e.g. Michalek et al. 2004; Goldberg, 1998; Bento et al., 2009; Jacobsen, 2013; Ou et al., 2018). In a given year, the automaker in our model plans ahead (up to 2030), and makes several decisions relating to three compliance mechanisms noted above (model variety, vehicle prices, and R&D investment), while trying to maximize profits subject to the policy.

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

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

Where, $Q_{tk}(P_{tk}, n_{ctk})$ is the quantity of each vehicle type k produced in t^{th} time and this quantity in turn is a function of price P_{tk}, and the number of models n_{ctk} of the vehicle type *k* produced domestically at time *t*. The automaker thus adjusts P_{tk}, n_{ctk} and C_{Itk} in equation (4) to maximize profits. The endogenous domestic production of models (n_{ctk}) gets added to the exogenous global production of models (n_{Gtk}) to give (n_{tk}). Here, (n_{Gtk}) is number of PEV models of technology *k* produced globally at time *t*, and (n_{tk}) is the total number of models seen by Canadian consumers of technology *k* at time *t* (equation 1). The quantity of vehicles of each type produced is assumed to equal the quantity demanded in the consumer choice model. As we note above, quantity demanded is in turn affected by vehicle prices and model variety supplied by the automaker. While studies such as Goldberg (1998), Bento et al. (2009), Jacobsen (2013) have included endogenous price feedbacks, the inclusion of model variety feedback is a novelty of AUM. The profit equation (4) also includes three cost terms (C_{Ptk}, C_{Rtk}, C_{Itk}), each of which is described briefly next.

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

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

Where C_{0tk} is the cost of production of a single vehicle of type *k* in time *t*, *a* is a scaling constant (Table 3.4) and $Q_{tk}(P_{tk}, n_{ctk})$ represents the total quantity of vehicles of type *k* produced domestically in time *t*.

Table 3.4: 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 PEV 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)
Vehicle stock turnover rate	5% annually	Statistics Canada (2020)

Knowledge Stock (*KS*), CVs in 2020	500 billion $CAD	Authors' calculation; based on Barreto and Kypreos (2004)
Knowledge Stock (*KS*), PEVs in 2020	3 billion $CAD	Authors' calculation; based on Barreto and Kypreos (2004)

The second cost term in equation (4), C_{Rtk}, indicates the total regulation costs related to policy. In this study, we consider regulation costs for a fuel economy standard (CAFE), low-carbon fuel standard, and ZEV mandate (policy scenarios detailed further in Section 3.3.3). We endogenously model the ZEV mandate and fuel economy standard as part of the profit function. For the ZEV mandate, the regulation costs are characterized by three design features:

- ZEV credits requirement: this dictates the minimum credits that the automakers must earn to avoid penalties.
- ZEV penalty: this indicates the fine per credit for non-compliance.
- ZEV credits per vehicle: based on their electric range, PEVs can be assigned either a single credit or multiple credits.

The regulation cost associated with the ZEV mandate is then modelled as $\rho_{ZEV} * (\emptyset_{t,ZEV} * Q_{t,Total} - Q_{t,ZEV})$, where ρ_{ZEV} is the penalty per ZEV credit below the stipulated quota, $\emptyset_{t,ZEV}$ is the minimum ZEV credits required by the quota (e.g. 4%), $Q_{t,Total}$ is the total number of vehicles sold by the automaker in time t , and $Q_{t,ZEV}$ is the total number of zero emission vehicles sold by the automaker in time *t*. Previous studies such as Ou et al. (2018) and Jenn et al. (2018) have treated the ZEV mandate as a hard constraint, thus forcing automakers to comply fully. Consideration of ZEV regulation costs as a part of automaker profit function is a novelty of this work – representing endogenous automaker response between compliance and non-compliance. For vehicle emission standards, similarly, the regulation cost is $\rho_{FE} * Q_{tk} * (Z_{t,FE} - Z_{t,k})$, where ρ_{FE} is the penalty, Q_{tk} is the number of vehicles of drivetrain technology *k* that are sold in time *t*, Z_{FE} is the vehicle emission requirement for time t, and Z_k is the emission level of vehicle *k* in time *t.* The total regulation cost is given by

$$C_{Rt} = \rho_{ZEV} * (\emptyset_{t,ZEV} * Q_{t,Total} - Q_{t,ZEV}) + \rho_{FE} * Q_{tk} * (Z_{t,FE} - Z_{t,k}) \qquad (6)$$

The third cost component in equation (4) above, C_{Itk} represents the Canadian automakers' R&D investment. We assume that the cost of production (C_{0tk}in equation 5 above) of vehicles produced in Canada can be in part influenced by the investment in research, C_{Itk} made by automakers domestically over time (apart from the exogenous decline in vehicle costs due to global efforts). As noted previously, the automaker model represents the Canadian auto industry as a whole, as if it was one aggregate automaker. While it is true that the Canadian auto industry is essentially a portion of global automakers, we intend to represent the Canadian contribution of R&D activity. While the global contribution is exogenous, the Canadian contribution is endogenous. For this novel formulation of R&D effects, we draw from Barreto and Kypreos (2004), Azevedo et al. (2013) and Chadwick (2016; personal communication) to represent the effect of R&D in the technological progress of innovative technologies. The automaker investment in research in time *t*, C_{Itk} endogenously adds to the knowledge stock KS_{tk} of the automaker as follows:

$$CC_{t-1k} = \sum_{t=1}^{t-1}[Q_{tk}(P,n)] \quad ; \quad KS_{t-1k} = \sum_{t=1}^{t-1}[C_{Itk}] \qquad (7)$$

Where knowledge stock, KS_{t-1k}, accumulates endogenously up to time *t-1* for technology *k* and along with the cumulative capacity (CC_{tk}) of vehicles produced affects the cost of vehicle production in time *t* as shown in equation (8).

$$C_{0tk} = \{\gamma_{tk} * C_{0t-1,k} * [CC_{t-1k}{}^{-LBD} + KS_{t-1,k}{}^{-LBS}]\} \qquad (8)$$

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

Thus, while on the one hand, investing in research increases automaker's costs in the present, on the other hand, such investment potentially reduces future production costs. When optimizing over the planning horizon, the automaker can trade-off between increased research costs in the present versus benefits from lower costs of production at a later date. The initial capital costs, initial knowledge stock, initial cumulative capacity, learning by doing (LBD), and learning by searching (LBS) values are exogenously specified in the model (Table 3.4). The cumulative capacity and knowledge stock for other modelling years are endogenously determined, where the cost of production (capital costs) is a function of both cumulative capacity and knowledge stock is known as the Two Factor Learning curve (2FLC) (Barreto and Kypreos, 2004).

Based on the above description, we can decompose the total change in automaker profits, resulting from a policy intervention, into five components.

(a) Sales: profits may drop if the total quantity of vehicles demanded by consumers (and hence sold) decrease, typically in response to higher prices.

(b) Average markup per vehicle: To induce PEV sales, automakers may offer these vehicles at a subsidized price. Although automakers could partially compensate for this cross-subsidy by offering conventional vehicles at a premium, a small net drop in average markup (across all vehicles) may result in profit drop. Downsizing effects (consumers shifting towards smaller vehicle classes) can contribute to both reduced sales as well as reduced markup. If a consumer preferring a big car finds that their preferred large vehicle is costlier than usual, they could completely forego the purchase, leading to reduced sales. Alternatively, they could shift to a smaller vehicle, which yields lower markups for the automaker on average.

(c) Higher production costs for PEVs which could increase the overall cost of production, resulting in a drop in profit.

(d) The regulation penalty costs: what automakers may have to pay for not complying with the ZEV mandate.

(e) Increased R&D investments as a result of the ZEV mandate policy, could also add to costs and may decrease profits.

We depict the decomposition of profits into these components in the results section (4.6).

We rely on Nykvist et al (2019) to obtain our best estimates of battery cost data (Table 3.3). In their study, costs are assessed by reviewing historical estimates and by creating scenarios for future battery pack costs to car manufacturers based on technological learning. As may be seen in equation 8, vehicle costs are influenced by a factor 'γ'. This g changes exogenously, in proportion to battery cost decline in Nykvist et al (2019). Accurate automotive industry data on R&D investment is difficult to find and has been largely gathered from grey literature (e.g. Automotive News, 2019; Reuters, 2019; CleanTechnica, 2019; TechCrunch, 2019; Deloitte, 2019; UCS, 2019).

A description of the model validation procedure and the model assumptions used for uncertainty analysis can be found in the Supplementary Information document.

3.3.3 Policy scenarios

To demonstrate the model, we analyze the effect of the ZEV policy (a nationwide ZEV sales mandate) relative to the baseline scenario.

a. **Baseline scenario:** no ZEV mandate is in place across Canada. The Baseline scenario, however, includes four policies currently in place in Canada:
    (i) Purchase subsidies – We model purchase subsidies as being offered to consumers by the Government across Canada, however these subsidies last from 2018 until 2020, when the subsidies are assumed to be removed. Our assumption at the time of writing this paper was that government budgets may be limited and may support subsidies for one-two years only.

(ii) Carbon tax – We include a nationwide carbon price on GHG emissions, increasing $10 a year from $30/tonne in 2020 until it reaches $50 a tonne in 2022, where it stays constant till 2030.

(iii) Low Carbon Fuel Standard (LCFS) – A national-level LCFS, is assumed to be in place. The LCFS is modelled as an exogenous 15% reduction in fuel carbon intensity by 2030.

(iv) Fuel Economy standard- A national-level fuel economy standard is in place requiring automakers to improve the fuel economy (and thus reduce the energy requirement per kilometre driven) of the vehicles produced, such that the average fuel economy improves linearly from 2.75 MJ/km in 2020 to 1.3MJ/km (~ 55 miles per U.S. gallon or alternatively 4.2L/100km) in 2025 and stays constant at that level until 2030.

We do not model other policies in place such as High Occupancy Vehicle lane access etc. which may be expected to have a negligible to small effect on ZEV market share (Melton et al., 2017).

b. **ZEV mandate scenario**: To examine the effect of the ZEV mandate policy, we consider a ZEV policy scenario such that the ZEV sales requirement is 5% of new market share in 2020, 15% in 2025 and 30% in 2030.

3.4. Results

We divide the results into six sections, sequentially presenting the Baseline estimates of vehicle costs and prices (4.4.1), PEV new market share results (3.4.2), Consumer PEV adoption (3.4.3). Automaker pricing strategies (3.4.4), Automaker supply strategies (R&D and model variety) (3.4.5), and Impacts to automaker profits (3.4.6).

3.4.1 Baseline estimates of vehicle manufacturing costs and prices

Fig. 3.3i depicts the vehicle manufacturing costs for the three different vehicle archetypes (conventional vehicle, plug-in hybrid with electric range of 60 km and battery electric vehicle with electric range of 380 km) estimated by the model for the Baseline scenario. The vehicle manufacturing cost (endogenous) estimates are similar to the calculations and forecast produced by market research studies such as Lutsey and Nicholas. (2019), and Islam et al. (2018). Fig. 3.3ii depicts the endogenously estimated vehicle retail prices over time. The vehicle prices determined by the model are similar to the exogenous prices assumed in other Canadian studies (e.g. Axsen and Wolinetz, 2018).

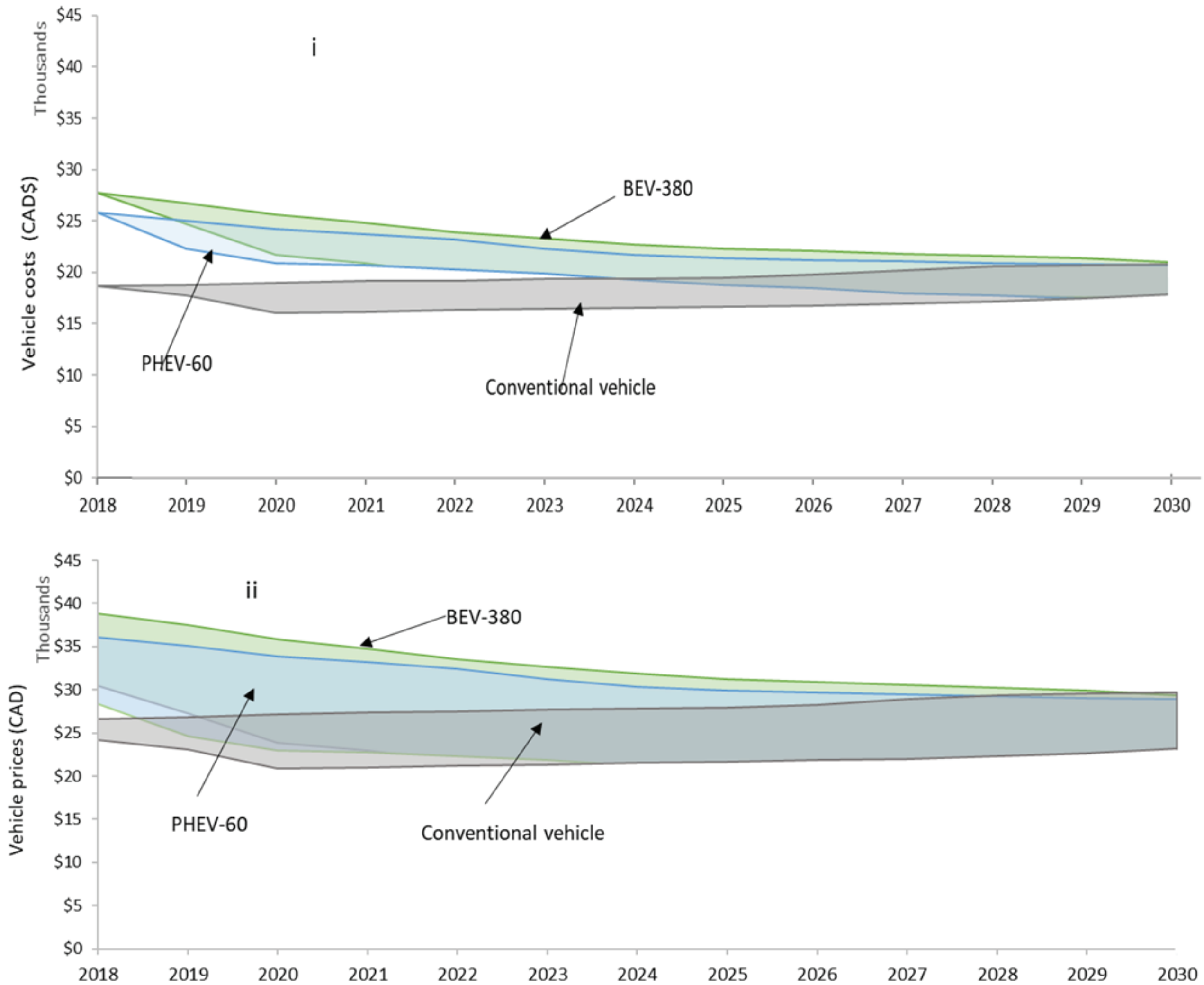

Fig. 3.3 Endogenously estimated vehicle manufacturing costs (Fig. 3.3i) and retail vehicle prices (Fig. 3.3ii) under the Baseline scenario, where the shaded region represents the uncertainty in results due to key parameters like battery costs, consumer preferences and price elasticity. We do not include median lines in this figure for the sake of clarity, specifically to avoid overlapping median lines.

3.4.2 PEV new market share results

Fig. 3.4 depicts the PEV new market share in the Baseline and ZEV mandate policy scenarios for 2018 to 2030 (where ZEV policy is implemented in 2020). The 2030 PEV market share in Canada is estimated to range between 6% to 12% in the Baseline. The 12% market share value (optimistic) represents the case where all input parameters assume optimistic values, while the 6% value (pessimistic) represents the case where all input parameters assume pessimistic values. (As noted, the optimistic and pessimistic assumptions are fully detailed in the Supplementary Information document.) Under the ZEV mandate policy, PEV sales are simulated to increase to 28% to 30% in 2030, either complying or mostly complying with the requirement. The shaded areas represent the uncertainty in the projection resulting from variation in key parameters. The fact that the uncertainty range is narrower for the ZEV mandate trajectory indicates that automakers choose to comply (or mostly comply) with the policy, even with relatively optimistic or pessimistic parameter assumptions.

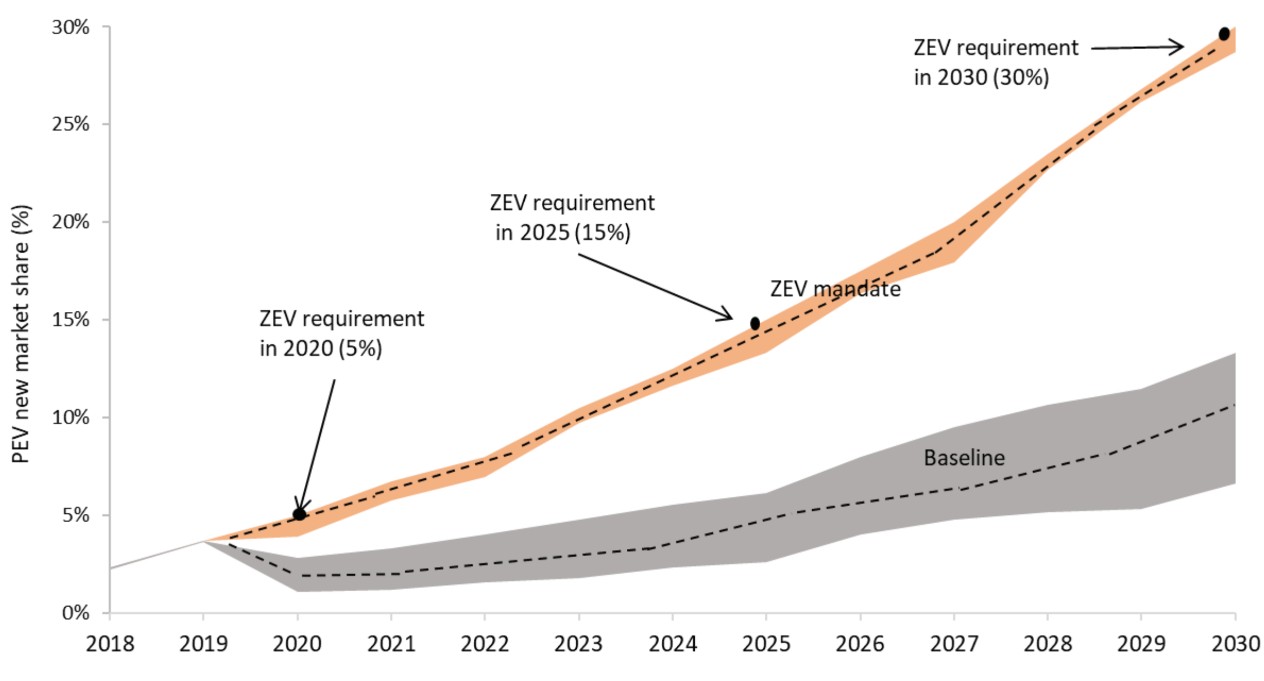

Fig. 3.4 PEV new market share under policy scenarios (with shading representing uncertainty in parameters)

Fig. 3.5i and 3.5ii depict the degree of sensitivity of the 2030 PEV market share results in the Baseline and ZEV mandate scenarios to each key input parameter variation, ordered from largest to smallest impact. The 2030 results are most sensitive to consumer preferences. Similar to other modelling studies (e.g. Axsen and Wolinetz, 2018), our results also indicate that recharging access, battery costs and model variety are other important factors that can influence the simulated PEV market share results.

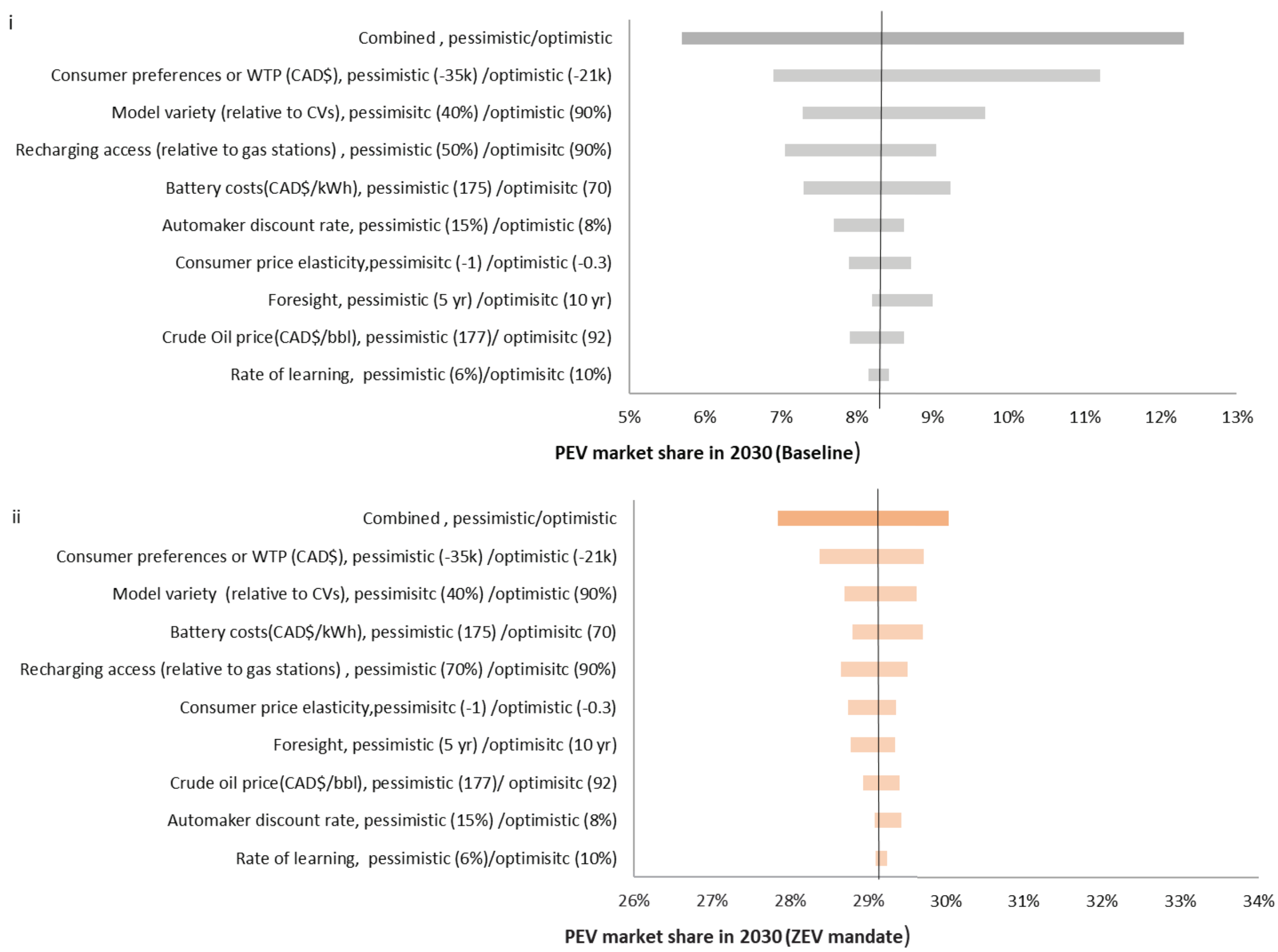

Fig. 3.5 Sensitivity analysis of PEV new market share in the Baseline (Fig. 3.5i) and ZEV mandate (Fig. 3.5ii) scenarios in 2030.

3.4.3. PEV adoption impacts

Fig. 3.6 depicts the distribution of new PEV market share across the three consumer segments. First, the results suggest that Enthusiasts constitute the bulk of PEV sales in 2030, both in the Baseline (~66%) and in the ZEV mandate scenario (~89%). The new market share of PEVs among Resistors and Mainstream buyers is much lower (~7% in the Baseline and ~12% in the ZEV mandate scenario). Second, the ZEV mandate noticeably increases the uptake of PEVs across all segments, though the effect is more pronounced for Enthusiasts. While the increase in PEV market share in 2030 among Enthusiasts is about 20%-point under the ZEV mandate, it is about 5-7%-point for the other consumers.

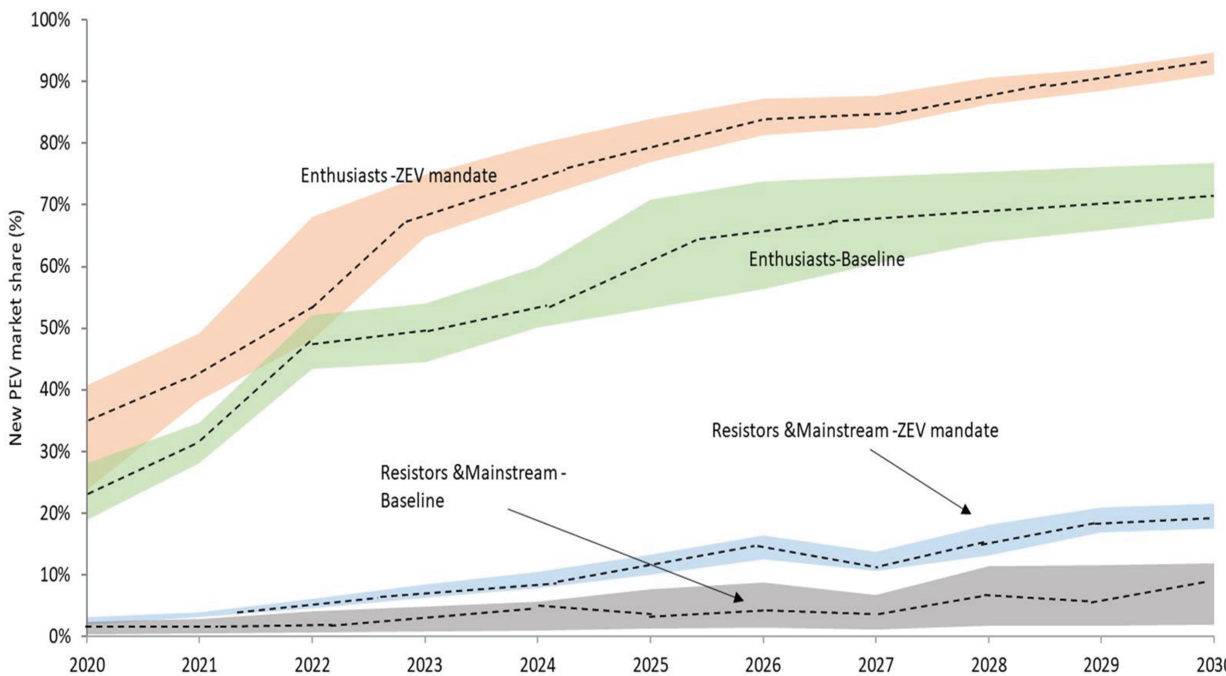

Fig. 3.6. PEV new vehicle market share by consumer segment- Enthusiasts (15%), Mainstream (50%) and Resistors (35%), under the Baseline and ZEV mandate scenario

Fig. 3.7 depicts the change in the consumers' choice of vehicle size that occurs due to the impact of the ZEV mandate policy. Small cars (compact and sedan) constitute a relatively higher proportion of the total PEV sales under the ZEV mandate. Out of all

PEVs sold, smaller cars are likely to be about 40% of the total sales in 2030 in the Baseline. This number rises by 5-7%-points to reach closer to 45-48% under the ZEV mandate. To comply with the ZEV mandate automaker increases vehicle prices for CVs and offer crass subsidies on PEVs. This causes some CV users to shift to PEVs. When this shift happens, some CV mini-truck/ SUVs users shift to PEV sedans, rather than shifting to the corresponding PEV mini-truck/SUV which are costlier. In our model, the bigger vehicles for PEVs are a lot costlier than the bigger vehicles for CVs. That is, the cost difference between mini-trucks/SUVs and sedans for PEVs is much higher than the cost difference between mini-trucks/SUVs and sedans for CVs. Thus, when the ZEV mandates is in place, it induces some downsizing of cars., creating some loss in consumer utility and automaker profits.

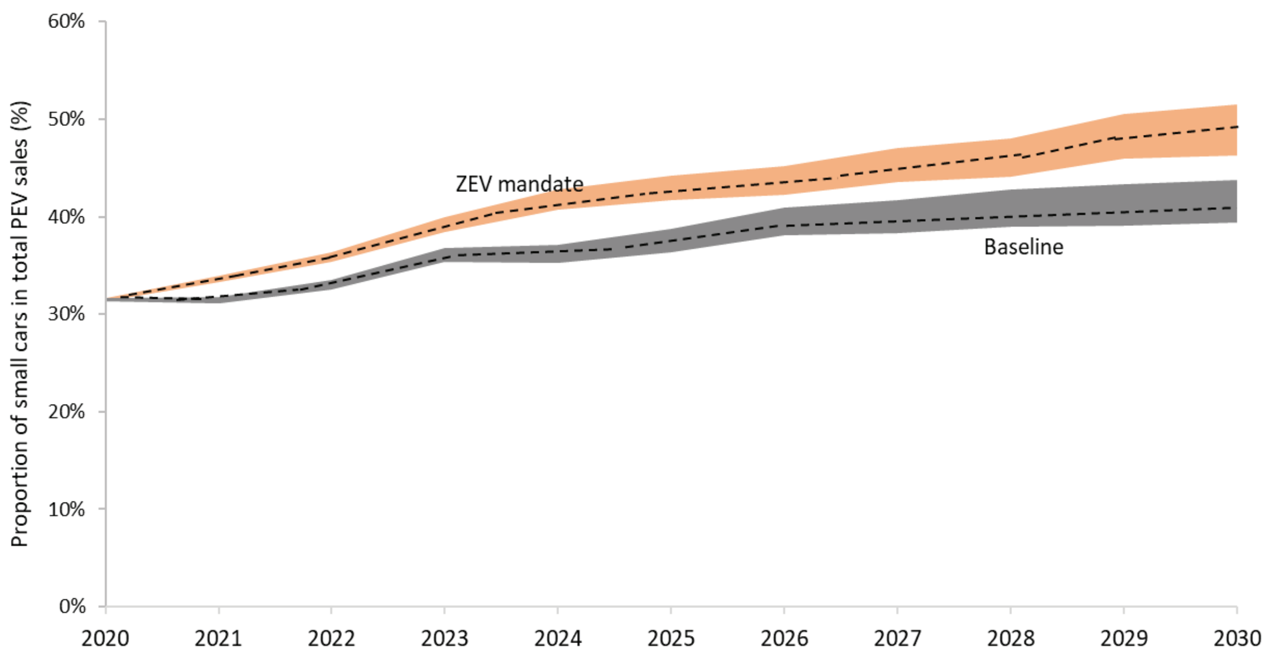

Fig. 3.7 Difference in the composition of the total PEV sales under the ZEV mandate and the Baseline scenario

3.4.4 Automaker pricing strategies

To better understand the effect of the ZEV mandate on the three compliance mechanisms under investigation in this study (i.e. intra-firm cross-price subsidies, R&D spending and model variety), we discuss each mechanism separately.

Beginning with price strategies, Fig. 3.8 depicts the endogenous change in automaker markups (markup of 1.1= 10% gross profit margin) for different vehicle technologies under the ZEV mandate and the Baseline scenarios. The markup is difference between the retail vehicle prices (as observed by the consumers) and the vehicle production costs (at the automaker's end). Thus, our notion of markups includes any intermediate markups as well, notably. dealership markups. In the Baseline scenario, the markups for conventional vehicles remain more or less constant at about 40% (markup of 1.4). Markups for both BEVs and PHEVs show a similar trend in the Baseline, starting at about 10% in 2020, but rise to nearly 40% by 2030. These markup results are similar to the trends indicated in the market research study by UBS (2017).

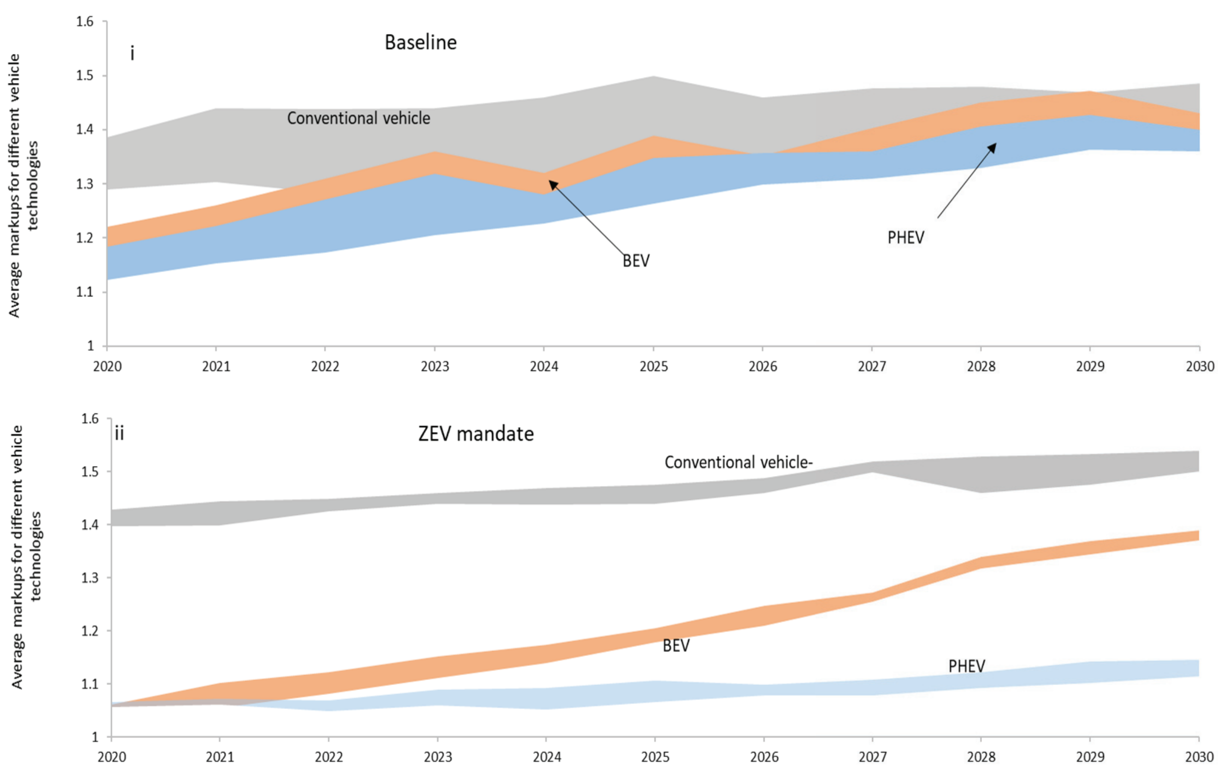

Fig. 3.8 Markups for CVs, BEVs and PHEVs under the (i) Baseline and (ii) ZEV mandate scenario. We do not include median lines in this figure for the sake of clarity, specifically to avoid overlapping median lines.

Under the ZEV mandate, : i) markups for CVs are higher, and ii) markups for PEVs (both PHEVs and BEVs) are lower. This implies that automakers cross-subsidize, i.e. charge a premium for conventional vehicles to partially compensate for the subsidies they have to offer to incentivize PEV sales. In the ZEV mandate scenario (Fig. 3.8ii), markups for PHEVs grow at a relatively slower rate, relative to BEVs. This happens because automakers prioritize PHEV sales to comply with the ZEV mandate. Consumers on average have a higher willingness-to-pay for PHEVs than for BEVs, as informed by the empirical Canadian data used in our model (for reference, see Table 3.2). Thus, automakers are likely to focus on PHEV sales to comply with the ZEV mandate, which is achieved mainly through reduced PHEV markups.

3.4.5 Automaker supply strategies (R&D and model variety)

Fig. 3.9 depicts the estimated R&D spending per vehicle (i.e. total R&D spending in each year, divided by total vehicles sold in each year) over time, under the Baseline and the ZEV mandate policy scenarios. The R&D spending is higher (>100% increase) under the ZEV mandate scenario (about $50/vehicle) compared to $20/vehicle in the Baseline in 2020. Under both scenarios, R&D spending is higher in the initial years and decreases over the remaining period. The quantitative accuracy of R&D spending estimates (in magnitude) is difficult to verify due to data unavailability. The qualitative nature of our results, however, appears reasonable on two accounts. First, research spending on PEVs increases under the ZEV mandate, which is supported by recent literature reviews (e.g. Hardman et al., 2018). Secondly, more R&D spending occurs in the initial years and decreases later on, which, too, is supported by market research analyses (e.g. UBS, 2017).

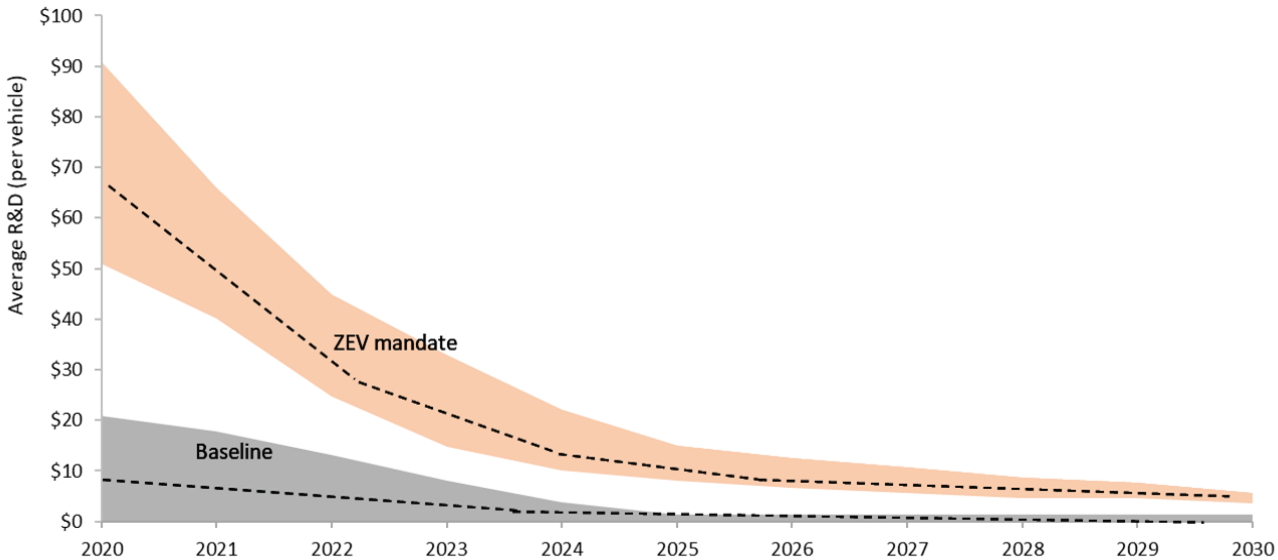

Fig. 3.9 Average R&D investment per vehicle (= total R&D in a year divided by the total no. of vehicles sold in a year) under the ZEV mandate and the Baseline scenarios

Fig. 3.10 depicts the total (Fig. 3.10i) and percentage change (Fig. 3.10ii) in the number of PEV models supplied by Canadian automakers in the ZEV mandate and the Baseline scenarios. As exogenously assumed, under the median case in the Baseline scenario, the number of PEV models in Canada increases from 28 in 2020 to 218 in 2030 (spread equally across all vehicle classes, available from all dealerships). Results indicate that the endogenous domestic increase in model variety under the ZEV mandate policy, is minimal (31 models in 2020, rising to 221 in 2030). In short, the simulation indicates that the domestic automaker is not heavily pushing new ZEV models under the policy scenarios. One reason is that Canada is a relatively small player in the global auto industry (representing 0.025% of global sales). Canadian automakers benefit from the increase in model variety contributed by the exogenous global growth in the number of models produced. With the cost assumptions we model, there is not strong enough incentive for automakers to increase the number of domestically produced models significantly. Presumably, the increase in costs for automakers would be higher if they produce new models, vis-à-vis adjusting markups to comply with the policy.

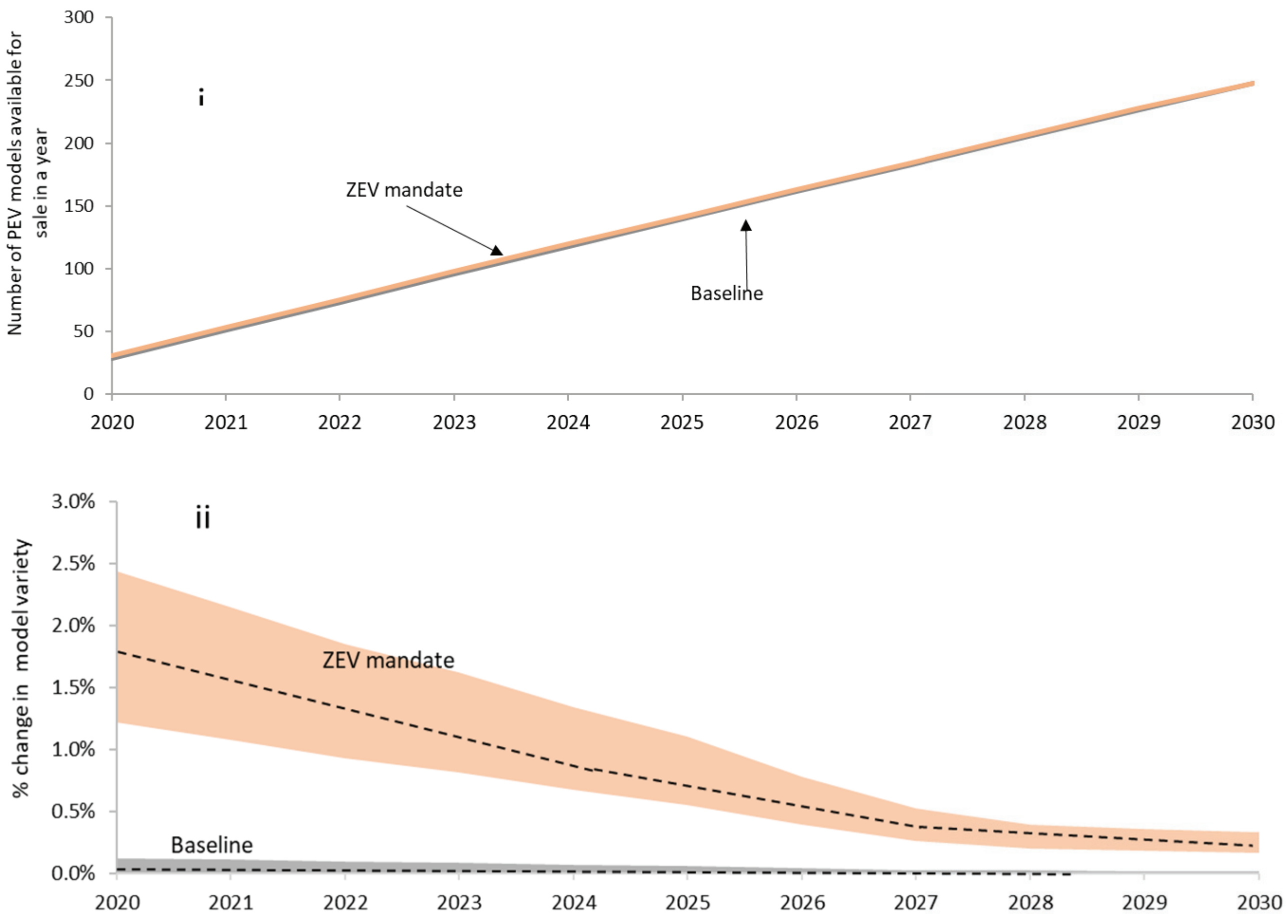

Fig. 3.10 Total number of models (or model variety) supplied by the automaker under the ZEV mandate and the Baseline scenarios (Fig. 3.10i). The corresponding change in the number of models (or model variety) that occurs under the ZEV mandate scenario relative to Baseline is depicted in percentage terms in Fig. 3.10ii.

3.4.6 Impacts to automaker profits

Fig. 3.11 depicts the total profits in the ZEV mandate and the Baseline scenarios, where the shaded area depicts the uncertainty in the total profit estimates. A few points need to be kept in mind before discussing these results. First, the profit values presented here are gross profits and not net earnings or profits, where we do not take account of operating or other expenses (e.g. marketing, insurance, payroll, rent). Second, unavailability of credible industry data limits the quantitative accuracy of the results. Third, this study depicts the ‘local’ or domestic automaker profits. Thus, a global automaker could opt for some losses in one region (e.g. Canada), but could compensate this with profits in other regions. Further, we do not consider leakage effects where automakers (global) could shift their product mix to comply with policy in one region. Having said this, our results appear to be in a reasonable range as we verify and show in Table S1 (Supplementary Information document).

Model results suggest that the Canadian automaker industry gross profits could reach anywhere between 21-26 billion CAD $ by 2030 in the Baseline. Compared to the Baseline scenario, total profits in 2030 under the ZEV mandate are likely to be in the range of 14-22 billion CAD$. We see that the ZEV mandate policy is likely to negatively impact automaker profits (with optimistic value of -7% and pessimistic value of -44% in 2030). The insight that the ZEV mandate policy may hurt automaker profits is supported by recent market research studies such as Nykvist et al (2019), though they do not provide any quantitative estimates.

However, the total automaker profits under the ZEV mandate (on average), are likely to be higher than the current profits. This implies that despite some drop in profits due to the ZEV mandate, automakers could still be better-off than they are today in terms of profits. We also note that there is huge uncertainty over the exact magnitude of the ZEV policy impact on automaker profits, due to variations in battery costs, consumer preferences, price elasticity, and discount rate (identified in the sensitivity analysis Fig. 3.12).

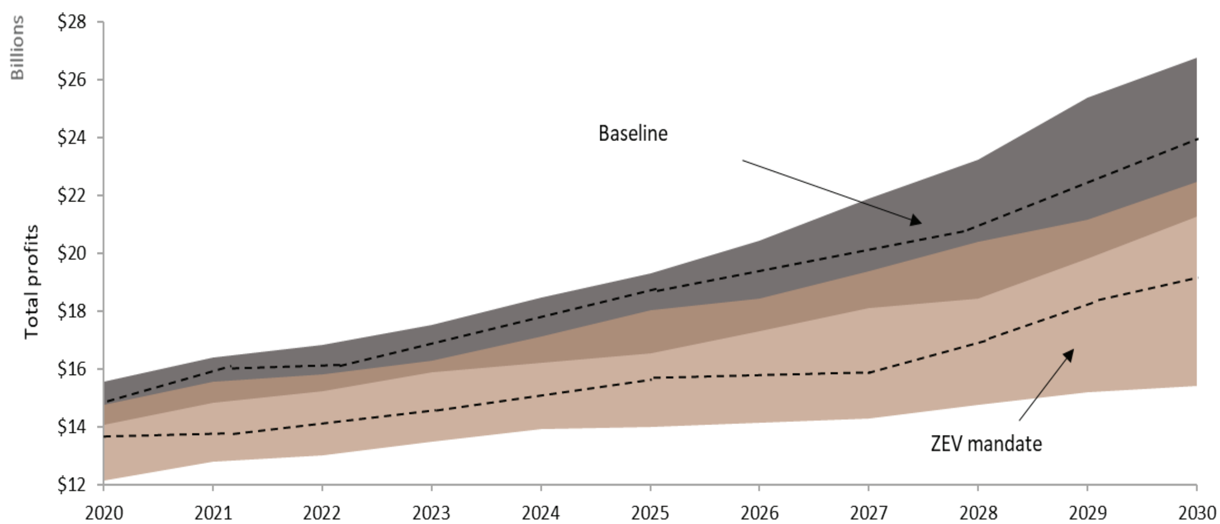

Fig. 3.11. Automaker profits (total) under the Baseline and ZEV mandate policy scenarios. The dotted line indicates the average case, and the shaded regions represent uncertainty in results due to parameters, where the sensitivity of results to parameters is depicted in Fig. 3.12.

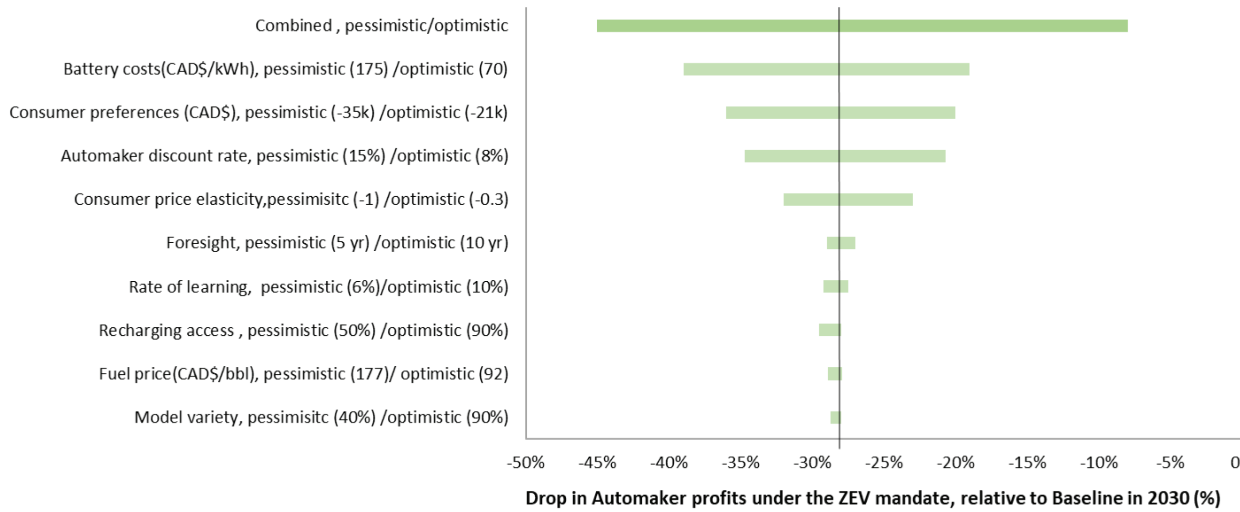

Fig. 3.12 Sensitivity analysis of the change in automaker profits under the ZEV mandate (relative to Baseline) in 2030

To better understand these profit impacts, Fig.3.13 depicts the median case breakdown of profit components, comparing the baseline and ZEV mandate scenarios. Reduced sales constitute the largest proportion (64%) of the profit drop. Sales are simulated to drop as consumers' preferred vehicles (CVs) and consumers' preferred vehicle class (SUVs and mini-trucks) are more expensive due to a premium charged by automakers. The assumed elasticities mean that an average increase in vehicle price will reduce the sales of new vehicles. The second largest factor (19%) is the drop in markup per vehicle, due to the higher proportion of PEVs in total sales and in part due to higher proportion of smaller cars in total sales (i.e. downsizing). Third is the higher cost of production (16% of profit loss). The contributions of R&D and the ZEV penalty are negligible (<1% each). Notably, a higher cost of production is a relatively smaller component of the drop in profits. In a typical scenario, PEVs reach cost parity with CVs somewhere in 2028-30, implying that production costs are not likely to be a big barrier in PEV uptake. The cost parity at the per-vehicle level however does not translate fully into total production costs, resulting in higher total production costs for PEVs. This is because higher total production costs for PEVs are largely attributed to building entirely new factories and battery production capacity, as also noted by Nykvist et al (2019). This effect is captured by the scaling parameter in the model (equation 5).

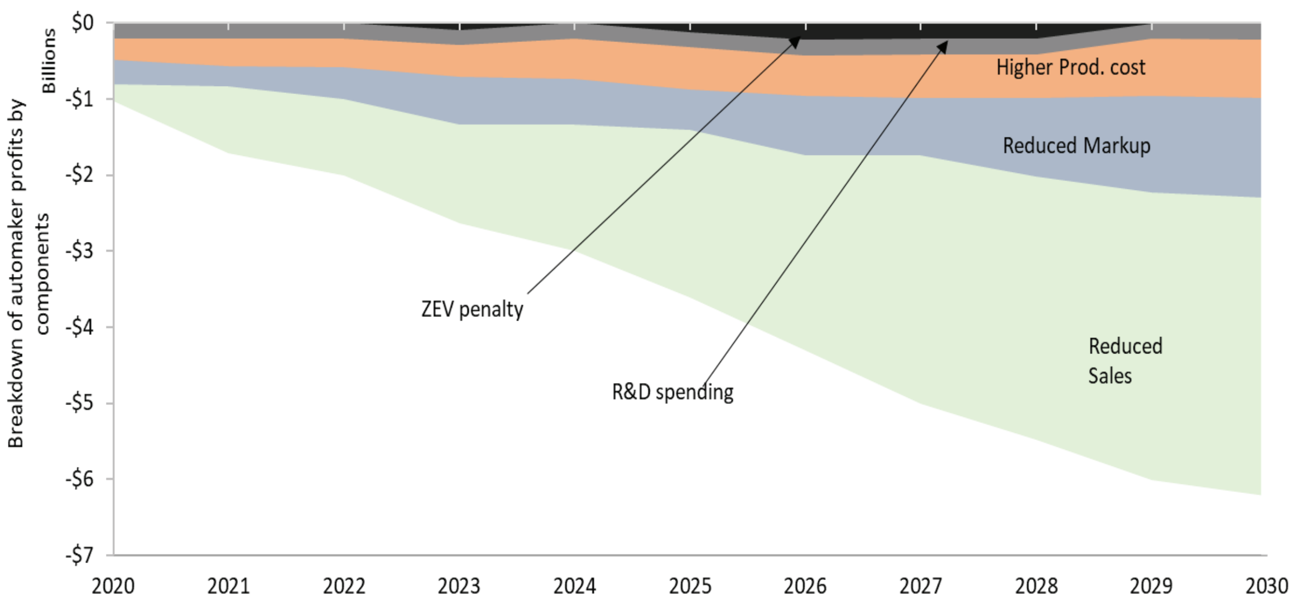

Fig.3.13 Breakdown of total profit drop (i.e. change in total profits under the ZEV mandate, relative to Baseline) for the median case into constituent components, namely (i) reduced sales (64%), (ii) reduction in average markup or profit margin (19%), (iii) higher production costs (16%), (iv) increased R&D spending (< 1%), and (v) penalty for ZEV mandate non-compliance (<1%).

3.5. Discussion and Conclusion

3.5.1 Main novelties and results

To fill an important gap in the literature on PEV technology adoption, we develop AUM, a model with explicit, endogenous representations of both consumers and an aggregated automaker agent. Our primary novelty is the incorporation of automaker perspective in a long-term technology adoption models for climate policy analysis (specifically for the ZEV mandate), which has rarely been attempted in the literature (Wolinetz and Axsen, 2018). Further, this model endogenously represents several system dynamics, including supply-side learning effects and changes in consumer preferences. Also, our application of the model is itself novel, which relates to examining the automaker compliance mechanisms in response to a supply-focused policy (in this case ZEV mandate).

Despite the limitations noted below, we believe AUM is suitable for a variety of policy-relevant applications. First, because it models policy response endogenously, AUM can be used to examine the design effects of a variety of supply-side policies. Second, the model can be used for studying policy interactions between policy instruments. Policies, often implemented simultaneously, may interact in a variety of ways (Bhardwaj et al, 2020), and our model can be used to quantitatively examine complementarity (and other interaction) effects between different policies. Such interactions can be missed by models that represent policies as hard constraints. Third, the model may also be used to analyse how automaker strategies respond to demand-side actions such as deploying infrastructure.

Further, the current focus of this modelling study was the Canadian automotive market. However, with minor modifications, the AUM model may be used to conduct similar analyses in other regions. To extend this model to other regions of the model, the few region-specific data requirements include: consumer preferences (e.g. ASC) to estimate the consumers' utility function; total vehicle sales data (by segment type) in the base year; learning by doing (and searching rate assumptions) for local automakers; and domestic automaker R&D spending in the base year. We hope to replicate this analysis on other regions in a future study.

Such insights can be highly policy-relevant, which we have illustrated with the present methodological exercise. First, our exploration indicates that if a ZEV mandate is added to Canada's existing policy mix, it could play a substantial role in increasing the ZEV vehicle market share in Canada. Second, such a policy is likely to have some negative effect on automaker profits, though such profits are still expected to higher in 2030 than they are today, assuming that demand for light-duty vehicles continue to grow to an extent.

Our results contribute to the existing PEV adoption literature. Similar to our findings, Jenn et al (2018), in their U.S. modelling study up to 2025, find that the ZEV mandate could negatively impact automaker profits, as do Ou et al (2018) for their modelling study up to 2020 for China. The two studies however consider the 'drop' in profits and do not comment on how total profits may evolve. Thiess et al (2016) using a systems dynamic model find that automakers' gross profits decrease slightly as EV uptake increases up to 2040, though they do not model the ZEV mandate explicitly.

We, however, also acknowledge and portray the substantial uncertainty in modelling results due to uncertainty in several key parameters, including the evolution of consumer preferences, battery costs, recharging infrastructure, and other more. A more thorough analysis of the ZEV mandate may involve examining the policy design effects in greater detail. This may involve considering multiple penalty levels for policy noncompliance and the effect of credit scheme used. Moreover, examining how the ZEV mandate may interact with other supply focussed policies over the long-term (e.g. fuel economy standards) is likely to yield richer insights on the suitability of the ZEV mandate, which has received little attention thus far (Jenn et al, 2018).

3.5.2 Limitations and future research directions

Our model demonstrates one way of including supply-side features, interactions with the demand-side, and endogenous representation of policy response. However, there is scope for a further work in improving the state of models representing technology development and adoption among light-duty passenger vehicles. Here we identify potential future research objectives with possible recommendations for addressing these gaps.

First is heterogeneity of automakers. We model just one aggregate automaker and acknowledge that this can be improved by adding multiple manufacturers and including competition between them. Such resolution could be particularly valuable for research exploring the impacts of supply-focused policy on specific automakers (say, domestic versus international automakers). Future model development may borrow from economics or engineering based studies. For example, Goulder et al (2012) consider seven auto manufacturers and consider competition between firms, using game theory principles. However, incorporation of multiple automakers and competition amongst them would add computational complexity to the model (Sullivan et al, 2009), and could come at the cost of other model features, such as dynamic optimization, or long-term foresight (Jacobsen, 2013). Thus, based on the specific research question, future technology adoption models may consider trade-offs between incorporating multiple firms or using simpler methods for representing heterogeneity. Arguably imports and exports may constitute a significant portion of vehicle sales in a country. However, as a simplifying assumption, we assume that domestic manufacturing is all for domestic consumers, and vehicles produced domestically are sufficient to meet domestic consumer demand. AUM could be further improved by explicitly representing the international linkages across countries, including imports and exports markets.

A second area for extension is endogenization of other supply side actors. In particular, representation of fuel suppliers would improve the model, including incumbent fossil fuel companies, as well as the potential actions of electric utilities and hydrogen providers. Such representation would be particularly important for representation of a low-carbon fuel standard (Lepitzki and Axsen, 2018), which in some jurisdictions is likely to interact with a ZEV mandate (such as California, Quebec and British Columbia). Similar efforts might also be directed to endogenize the decisions of infrastructure providers.

A third area is representation of non-financial factors affecting automaker decisions. Examples include risk aversion due to uncertainty, and political or social costs of non-compliance with a policy (Jacobsen, 2013; Kang et al, 2018). Kang et al (2018) present one way of including the effect of risk and uncertainty in gas prices on automaker decisions by choosing a multi-objective function where they maximize expected net present value of profits and simultaneously minimize the variance in profits over time. Jacobsen (2013) examines the effect of socio-political costs (e.g. due to lost reputation) that automakers perceive for not complying with policy. Jacobsen econometrically estimates the likely socio-political costs incurred by different groups of US automakers from historical policy compliance behaviour. Adding these non-financial factors is likely to add greater realism in representation of automaker behaviour in technology adoption models.

Fourth, and related, is incorporation of more empirical supply-side data. We acknowledge that reliable vehicle manufacturing cost is difficult to obtain. Future research may do more to collect more authentic automotive industry research investment data. While we have had to rely on grey literature and estimates to populate the model, there have been few examples of primary collection of empirical data on the supply side. For example, Rivers and Jaccard (2005) estimate a discrete choice model of the industrial steam generation technology decision from a survey of 259 industrial firms in Canada. As noted above, Jacobsen (2013) made use of econometric data to estimate political costs for automaker firms to inform his model. More such attempts are needed in future research.

Chapter 4. How does a zero-emissions vehicle (ZEV) mandate impact automakers and consumers? Simulating Canada's light-duty vehicle sector using the AUM model[5]

Abstract

While recent studies simulate policy impacts on zero-emissions vehicle (ZEV) sales with respect to consumer adoption, few examine how changes in the design of the ZEV mandate policy will affect new vehicle market share. Here we use AUM to further explore the case of a ZEV mandate in Canada, examining the impacts of different policy designs (with varying non-compliance penalties and credit schemes) on ZEV adoption, consumer surplus and industry profits. We find that a higher penalty for non-compliance (CAD$ 10k per credit) is needed to achieve the 30% by 2030 policy target. --A lower penalty (CAD $2.5k -7.5k per credit) results in 14-26% ZEV market share by 2030. Compliance is further impacted by the allocation of ZEV credits. For example, if plug-in hybrid vehicles earn the same credits as battery electric vehicles, policy compliance is more likely but negative impacts to profits and consumer surplus are increased. Finally, allowing automakers to bank credit softens the policy impact on profits and increases automaker compliance in initial years.

[5] This paper was presented at the Transportation Research Board Annual Meeting 2020, selected after a peer-review process. It is currently at the Revise and Resubmit stage in Transport Policy. Drs. Axsen, and McCollum, helped in the writing (review and editing) of this paper, as well as guided me during the conceptual design stage.

1 Introduction

While recent studies simulate policy impacts on zero-emissions vehicle (ZEV) sales with respect to consumer adoption, few examine how changes in the design of the ZEV mandate policy will affect new vehicle market share. In this paper we consider the case of the ZEV mandate policy in Canada to examine the impacts of different policy designs (with varying non-compliance penalties and credit schemes) on adoption, consumer surplus and profits. We use the Automaker- consumer model (AUM), to conduct our analysis. We describe the AUM model in greater detail elsewhere (Bhardwaj et al, 2021). In this paper we use the term ZEVs to refer to vehicles that have zero tail-pipe emissions such as plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) – we do not presently include hydrogen fuel cell vehicles.

ZEV mandates are a policy that arguably have been quite effective in promoting ZEV sales in recent years (Lutsey et al, 2015; Melton et al, 2017), and that can help a region to achieve long-term (2030 and 2050) GHG emissions mitigation targets (Sykes and Axsen, 2017; Lepitzki and Axsen, 2018). A ZEV mandate was first implemented by California in 1990 (and 10 other US states), and versions have more recently been implemented in China and Canada (Quebec and British Columbia). The ZEV mandate requires automakers to produce (for sale) a certain percentage of their total vehicle fleet annually to be ZEVs. Each ZEV produced earns some credits which counts towards the ZEV requirement. For example, California had a ZEV credit requirement of 4% in 2020 rising up to 22% by 2025. British Columbia, Canada, more recently introduced a ZEV mandate that follows California's requirements until 2025, but then requires 30% ZEV new market share in 2030, and 100% by 2040.

Despite the relatively long history of the California ZEV mandate, quantitative examination of ZEV mandates remains a small literature space (e.g. Sykes and Axsen, 2017; Greene et al, 2014;), with the automaker perspective often ignored. In particular, technology adoption models which have more commonly been used to study the ZEV mandate (e.g. Greene et al, 2014; Axsen and Wolinetz, 2018), do not represent the automaker endogenously, or in any detail. Some studies that do consider automaker perspective (e.g. Walther et al, 2010; Thies et al, 2016), do not consider how automakers may endogenously respond to changes in the design features of the policy. Ou et al. (2018) provide one of the very few examples of technology adoption models that endogenously represent an automaker perspective, examining the effects of a ZEV mandate (combined with a fuel economy standard) in China. The authors develop a model which explicitly represents an optimizing aggregate automaker and examine the effects of the dual policy on ZEV market share. However, they examine only the short-term effects of the policies (2016-2019), thus ignoring learning effects and they assume homogenous consumers. Moreover, they treat the ZEV requirement as a constraint, forcing 100% compliance from automakers, which may not happen in the real world.

Further, no published studies, to the best of our knowledge, have explored the impacts of different designs of the ZEV mandate. Potentially important design features include the magnitude of non-compliance penalties, as well as the credit schemes (including “banking”, and credits assigned per vehicle type). In current North American versions (California, Quebec and British Columbia), a penalty of US$ 5000 per credit is imposed for non-complying automakers – though it is unclear if such a penalty is strong enough for more ambitious ZEV sales targets (i.e., 2030 or later). Further, under California-style ZEV mandates, different vehicle types earn different number of credits. For example, BEVs on average earn higher (between 1 and 4) credits than PHEVs (between 0.5 and 1.2), because BEVs have a longer electric range. Another design feature is the potential for credit “banking”, which allows manufacturers to carry over excess credits from one year to the next. Little is known about the impacts or importance of these various design features. We intend to contribute to the relatively sparse ZEV modelling literature by examining the effect of ZEV policy design features (i.e. penalty, banking and credit scheme) on new vehicle market share, consumer surplus and automaker profits.

We attempt to answer the following research questions: will a national ZEV mandate in Canada help achieve the 30% by 2030 target set by the Government? In particular, how is compliance with the policy affected by policy design (penalty, banking and credit system)? The objectives of this work are:

- #1 To simulate how changes in Zero Emissions Vehicle (ZEV) mandate penalty affect market uptake of plug-in electric vehicles, consumer surplus and automaker industry profits
- #2 To simulate how alternative versions of ZEV mandate credit system affect new plug-in electric market share and policy impact on profits and consumer surplus.
- #3 To simulate how the option of banking credits under the ZEV mandate affects new plug-in electric market share and policy impact on profits and consumer surplus.

The organization of the paper is as follows: Section 4.2 provides the details of the model used to conduct this study as well as describes the scenarios used to analyse results. Section 4.3 presents the results. Section 4.4 concludes and discusses policy implications of the results.

4.2 Model

To avoid repetition, I do not include Sections 4.2.1, and 4.2.2 here (which were originally part of the paper submitted to Transport Policy). These sections are essentially the abridged versions of the consumer and automaker component respectively, detailed descriptions of which are already presented in chapter 3 (sections 3.3.1 and 3.3.3).

4.2.3 Policy scenarios

To analyze the effect of the various design features of a nationwide ZEV sales mandate, we compare ZEV mandate policy scenarios relative to the baseline scenario. **Baseline scenario:** no ZEV mandate is in place across Canada. The Baseline scenario, however, includes four policies currently in place in Canada:

(i) Purchase subsidies – We model purchase subsidies as being offered to consumers by the Government across Canada, however these subsidies last from 2018 until 2020, when the subsidies are assumed to be removed.

(ii) Carbon tax – We include a nationwide carbon price on GHG emissions, increasing $10 a year from $30/tonne in 2020 until it reaches $50 a tonne in 2022, where it stays constant till 2030.

(iii) Low Carbon Fuel Standard (LCFS) – A national-level LCFS, is assumed to be in place. The LCFS requires a 15% reduction in fuel carbon intensity by 2030.

(iv) Fuel Economy standard- A national-level fuel economy standard is in place requiring automakers to improve the fuel economy (and thus reduce the energy requirement per kilometre driven) of the vehicles produced, such that the average fuel economy improves linearly from 2.75 MJ/km in 2020 to 1.3MJ/km (~ 55 miles per U.S. gallon or alternatively 4.2L/100km) in 2025 and stays constant at that level until 2030.

We do not model other policies in place such as High Occupancy Vehicle lane access etc. which may be expected to have a small effect on market share (Melton et al., 2017).

ZEV mandate penalty scenarios: To examine the effect of the ZEV mandate policy, we consider ZEV mandate scenarios such that the ZEV credit requirement is 5% in 2020, 15% in 2025 and reaches 30% by 2030. To address the first research objective, we consider four ZEV policy scenarios to analyse the effect of increasing ZEV penalty on new light duty vehicle market share and auto-industry profits. These penalty levels include $2,500/credit ($2.5k penalty scenario in the results section), $5,000/credit ($5k penalty scenario), $7,500/ credit ($7.5k penalty scenario) and $10,000/ credit ($10k penalty scenario). All values are in Canadian dollars. For all these scenarios we assume an Equal credit scheme where all ZEVs produced earn one credit each. Also, no banking of credits is assumed in all these scenarios.

ZEV credit scheme scenarios -To address the second objective (i.e. to compare the effects of different credit systems), we consider two ZEV credit scenarios: California style (2 credits per BEVon average; 0.75 credits per PHEV on average), and Equal credit scenario (one credit each for all ZEVs), in the results section. To aid comparison, a ZEV penalty of $10,000/ credit is assumed for oth these scenarios and the ZEV credit requirement is 5% in 2020, 15% in 2025 and reaches 30% by 2030. No banking of credits is assumed in these two scenarios.

For the third research objective (i.e. to assess the effects of banking credits), we consider a second category of ZEV mandate scenarios. For the Equal credit and California-style scenarios mentioned above, we consider the case where automaker is allowed to bank credits over time. As noted in the methods section, this means that extra credits earned in a year can be used to meet the credit requirement in a later year. As a simplifying assumption, we assume that an extra credit earned in the first year can be used in any of the later years upto 2030. The Equal credit Bank scenario represents the Equal credit scheme with banking and the California style Bank scenario represents the California -style scheme with banking in the results section.

4.3. Results

In this section we first examine the effects of the different ZEV policy penalty scenarios on ZEV new market share out to 2030, including the impact on automaker profits (Section 4.3.1). Then, we examine the impacts of the ZEV credit scheme on ZEV new market share, consumer surplus, automaker profits as well as the relative distribution of BEVs and PHEVs on the total ZEV market share (Section 4.3.2). Next, we examine the impacts of the credit banking scheme on ZEV new market share, consumer surplus and automaker profits (Section 4.3.3). Note that in these initial sections we present our results as point estimates; this is for the sake of clarity, hence these results are largely illustrative of the processes in the model. We then present an uncertainty analysis in section 4.3.4, in order to exhibit how our results are sensitive to key parameter assumptions.

4.3.1. The impacts of ZEV mandate penalty

Fig. 4.3 compares ZEV new market share under the Baseline and the four ZEV penalty scenarios (all with Equal credit scheme). In the Baseline scenario with no ZEV mandate in place, we see that ZEV new market share initially peaks at around 4% in 2019. Once the financial incentives are removed in 2020, new market share drops to 2%, and then grows slowly to 8% by 2030. The new ZEV market share is the highest under the $10k penalty scenario and almost reaches the Government target of 30% ZEVs by 2030. The new ZEV market share is slightly lower at 27% for the $7.5k penalty scenario and much lower at about 20% for the $5k penalty scenario. The $2.5k penalty scenario is somewhat higher than Baseline with 13% new PEV market share by 2030. These ZEV scenarios demonstrate that ZEV sales could be highly dependent on the value of penalty imposed on non-compliance. This result corroborates findings by Wesseling et al (2015), who suggest that compliance by U.S. automakers increased with increased stringency, in an empirical case study of the ZEV mandate for the California auto market. Further, these results appear to suggest that the current policy mix with a high penalty ($7,500 or higher at $10,000/credit) ZEV mandate may be expected to come close to the designated policy target in 2030 and beyond. However, with lower penalties, automakers may elect to under-comply, and pay some amount of the penalty.

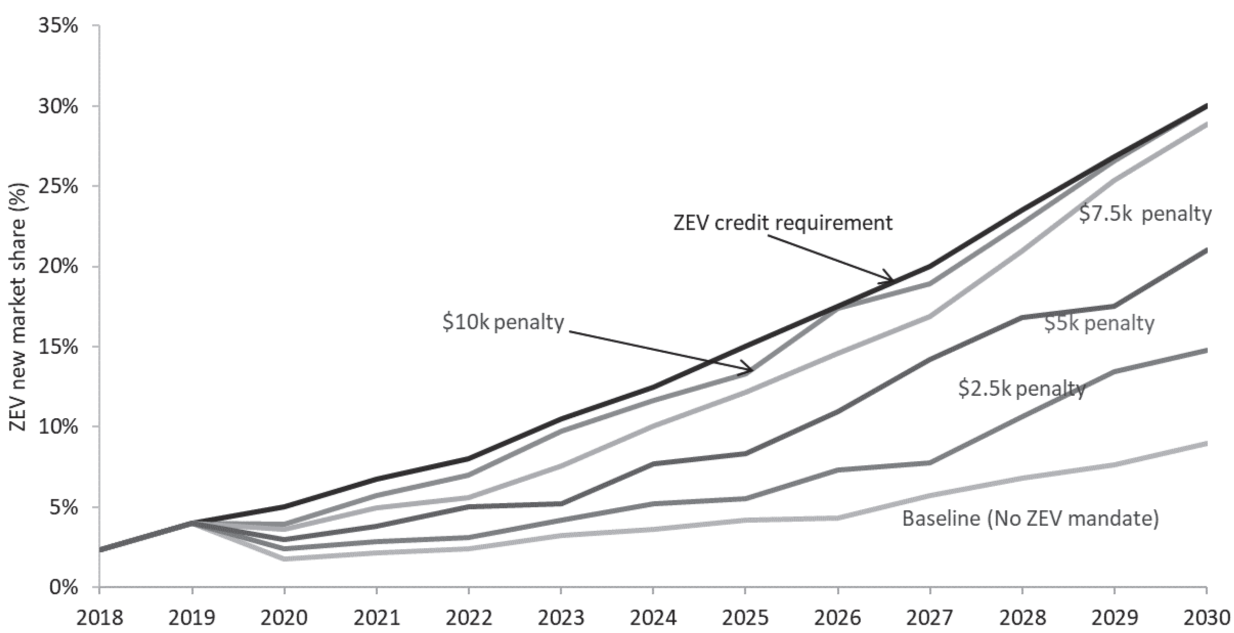

Fig.4.3. ZEVs new vehicle market share in Canada under the Baseline and ZEV penalty scenarios (all with Equal credit scheme)

Fig.4.4 depicts the percentage change in consumer surplus under the four ZEV penalty scenarios relative to the Baseline (all with Equal credit scheme). Relative to the Baseline scenario, consumer surplus drops further with an increasing ZEV penalty. Drop in consumer surplus varies between a low of 11.8% under the $2.5k ZEV penalty to a high of 25.1% under the $10k ZEV penalty in 2030. Higher penalties force the automaker to push more PEVs to consumers. This is largely achieved by increasing prices for conventional vehicles and subsidizing PEVs. Since consumers are pushed away from their preferred vehicles (i.e., conventional vehicles), this leads to a drop in consumer surplus.

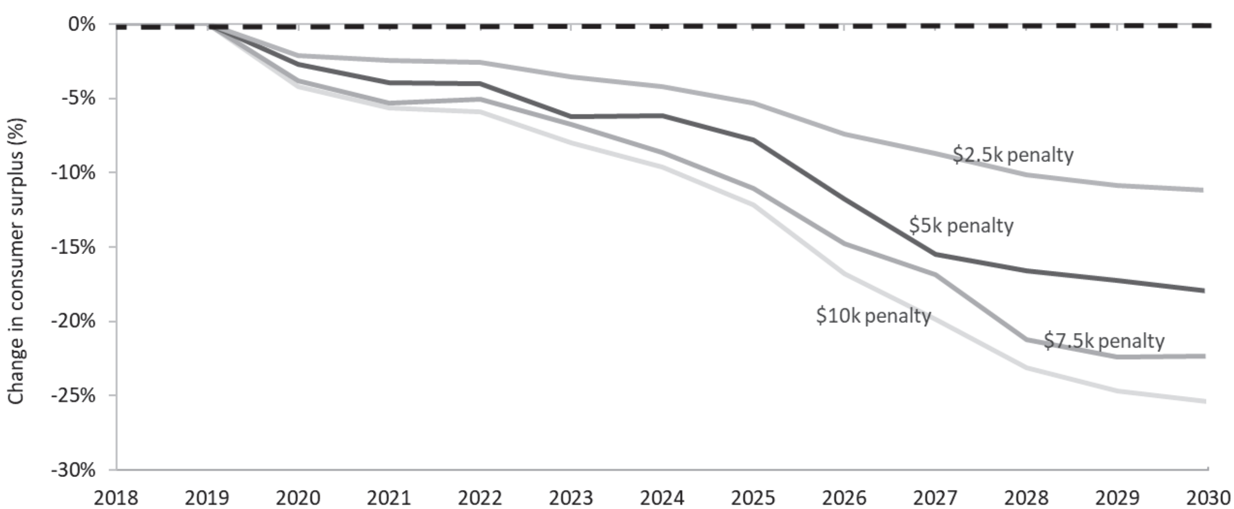

Fig. 4.4 Percentage change in consumer surplus under the ZEV penalty scenarios relative to the Baseline (All scenarios with Equal credit scheme)

To provide an additional perspective, we analyse the impacts of ZEV mandate penalty scenarios on automaker profitability. Fig. 4.5 summarizes the policy impacts on automaker industry profits for each ZEV penalty scenario. Fig. 4.5i gives total profits, while Fig. 4.5ii presents the drop in profits relative to the Baseline (All values in Fig. 4.5ii are shown in percentage change). As expected, the policy impact on profits increases progressively under the ZEV scenario with increasing penalty. The drop in profit is about 9.8% ($2.5k penalty scenario), 16.4% ($5k penalty scenario), 25.1% ($7.5k penalty scenario) and 28.3% ($10k penalty scenario) respectively. Note that these profit values are a function of our assumptions about change in consumers' preferences and supporting infrastructure (e.g. charging stations, global decline in cost assumptions) over time. However, proportionally comparing the impacts across penalty levels is more insightful – for example, where a $10k penalty might have 12%-points more impact than a $5k penalty, but only 3%-points more impact than a $7.5k penalty.

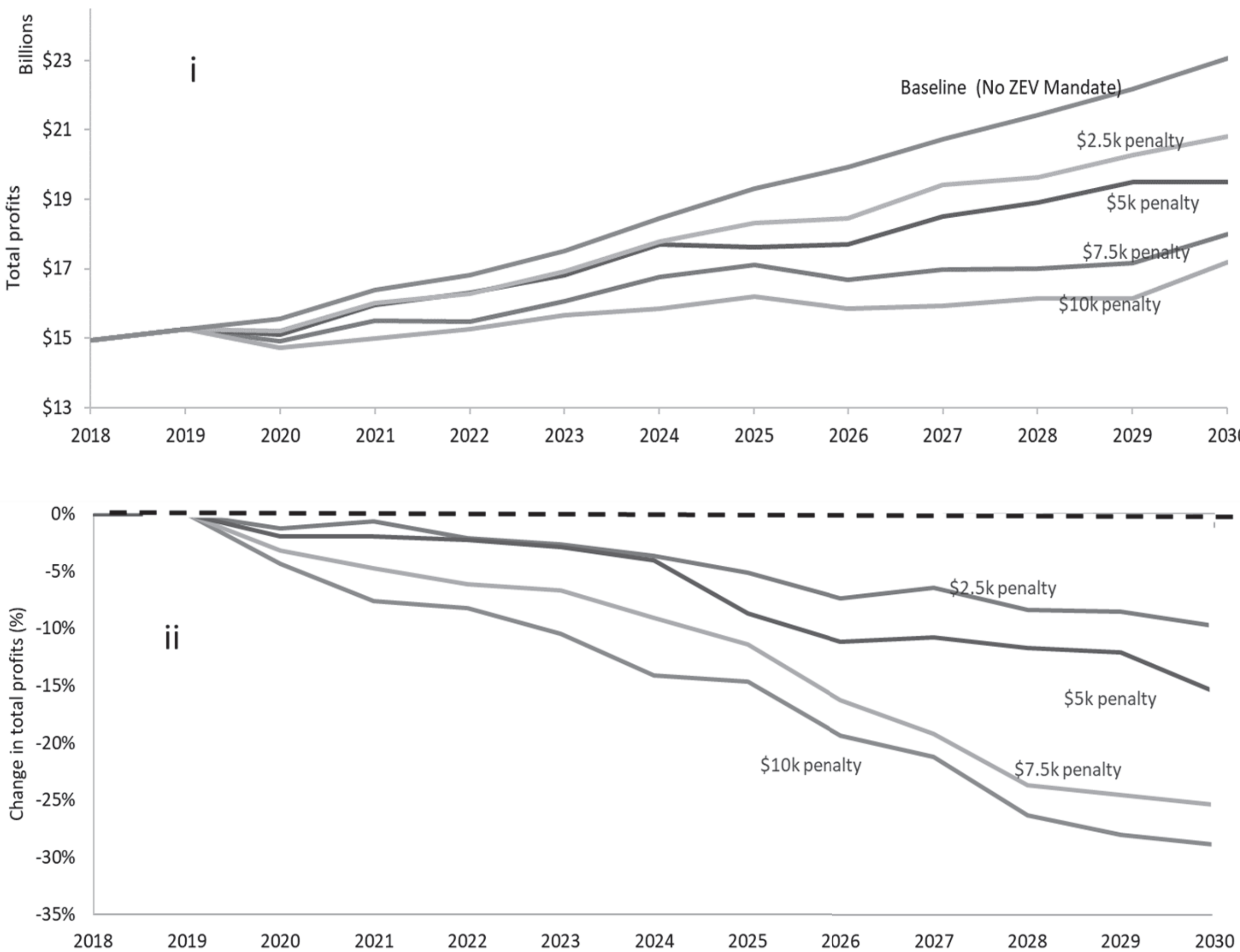

Fig. 4.5 Percentage and total change in automaker industry profits under the ZEV penalty scenarios relative to the Baseline (All scenarios with Equal credit scheme). All values in Canadian dollars.

4.3.2. The impacts of ZEV credit scheme

Fig. 4.6 depicts the difference in new ZEV market share between the Equal Credit and California style credit schemes (both with $10k ZEV penalty/ credit). The total ZEV market share is higher under the Equal Credit scenario with substantial differential (~10%-points in 2030). While the ZEV new market share almost reaches the ZEV requirement under the Equal Credits scenario, it is consistently lower than the requirement for the California style scenario. The direction of this result is expected because, under the California style scenario, automakers earn more than one credit for some vehicles (namely BEVs). Thus, automakers can meet the ZEV policy requirement with fewer ZEVs produced and sold. This result would suggest that an Equal Credit scenario is preferable if the priority of the policy is to increase the total number of ZEVs on the road, whereas the California scheme is perhaps preferable if the priority is to incentivize sales of particular types of ZEVs (e.g., BEVs with their 'bonus' credits), even if the total number of ZEVs sold would be lower.

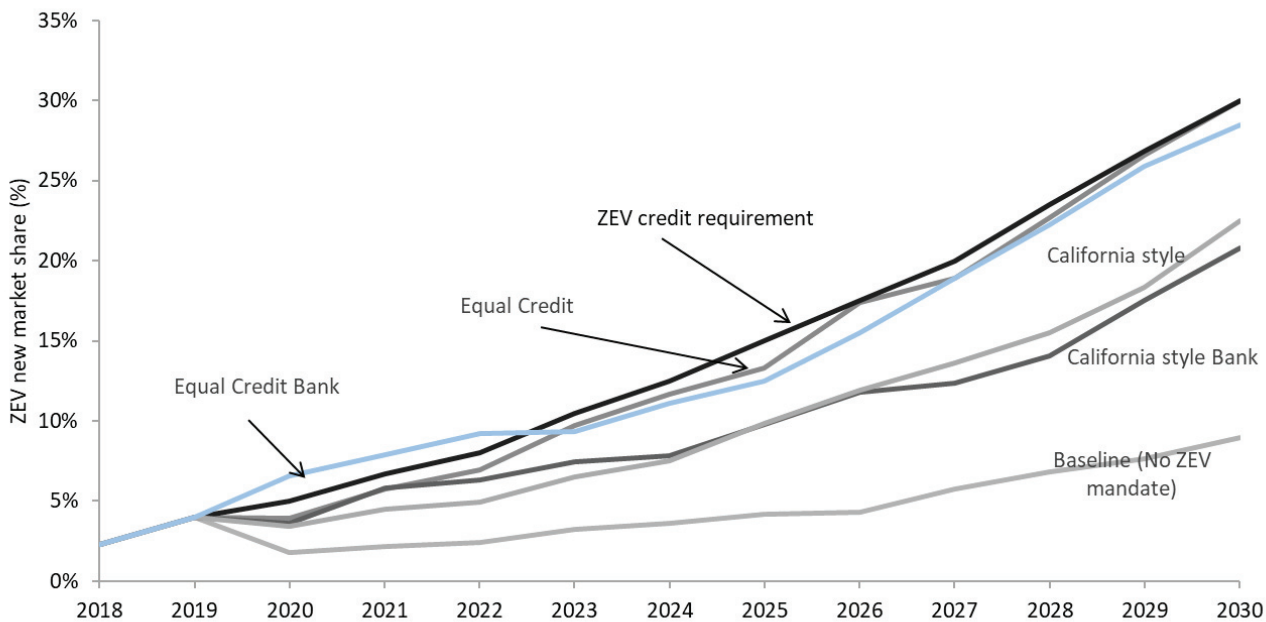

Fig. 4.6 ZEVs new vehicle market share in Canada under the Baseline, ZEV Equal Credit scenario (with and without Banking) and California style scenario (with and without Banking) (all credit scenarios with same ZEV penalty of $10k/credit)

Fig.4.7 compares the effect of the two credit schemes on the distribution of different ZEV technologies by depicting the PHEV portion of total ZEV sales under Equal Credit and California-style scenarios. The results indicate that PHEVs achieve noticeably higher (~15%-points) market share under the Equal Credit scenario (compared to the California style scenario where BEVs and PHEVs market share are somewhat more comparable.). It follows that the proportion of BEVs in the total ZEV mix is higher under the California style credit scheme. PHEVs typically have lower cost of production and higher acceptance among majority of consumers compared to BEVs. Thus, if PHEVs earn as many credits as BEVs (as is the case in Equal Credit scenario), there is rationale for automakers to push for higher PHEV sales. The reverse is the true under the California style scenario. This logic may explain the difference in PHEV market share under the two credit scenarios.

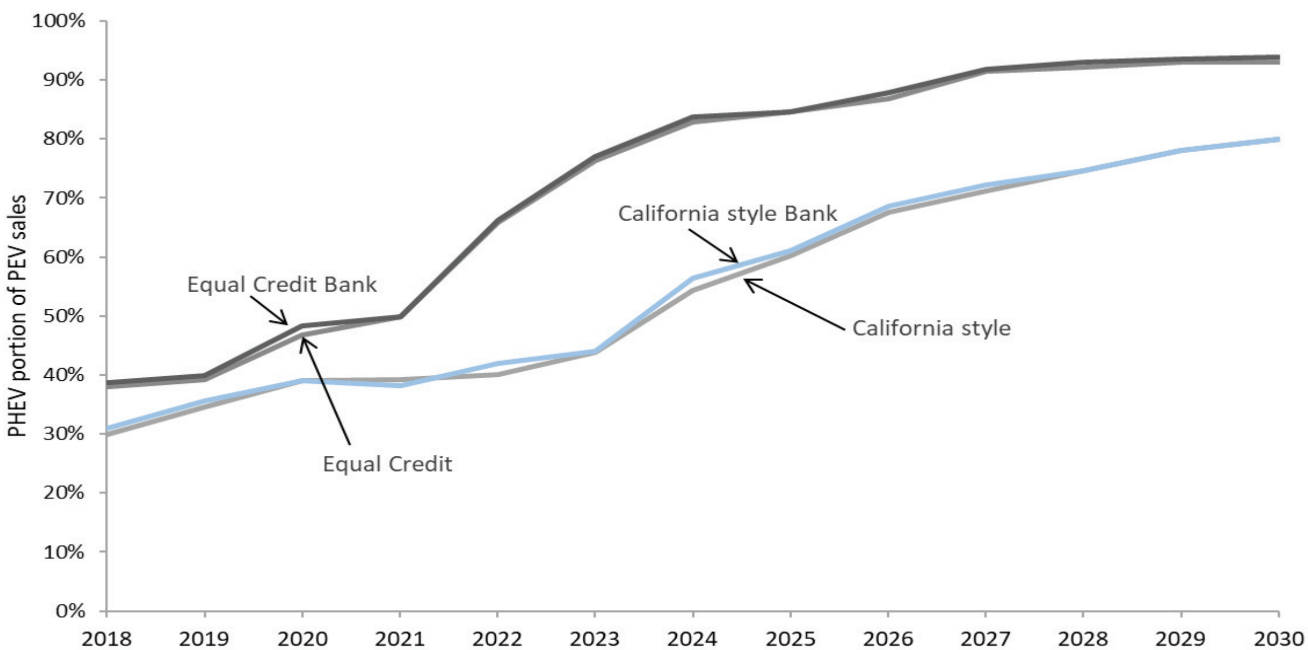

Fig. 4.7 PHEV sales as a percentage of the total ZEV new market share under the ZEV Equal Credit scenario (with and without Banking) and California style scenario (with and without Banking) (all scenarios are with same ZEV penalty of $10k/credit)

Fig. 4.8 depicts the change in annual automaker industry profits (compared to Baseline) over time under the ZEV Equal Credit and California style credit scenarios. The ZEV penalty for both credit scenarios is $10k/credit. The policy impact on profits under the California style scheme is consistently lower than the Equal credits scheme for majority of the modelling horizon, with the difference being ~5%-points in 2030. This is potentially because automakers can avoid greater amount of penalty by producing fewer ZEVs (since BEVs on average get higher credits per vehicle) under the California style scheme. As a point of comparison with empirical findings, the breakup of PHEV vs BEVs in California was nearly similar in the initial years (CNCDA, 2018), a finding estimated by our model as well. Further, the PHEVs sale composition is projected to increase and be higher than 60 percent by 2025 (CARB, 2017).

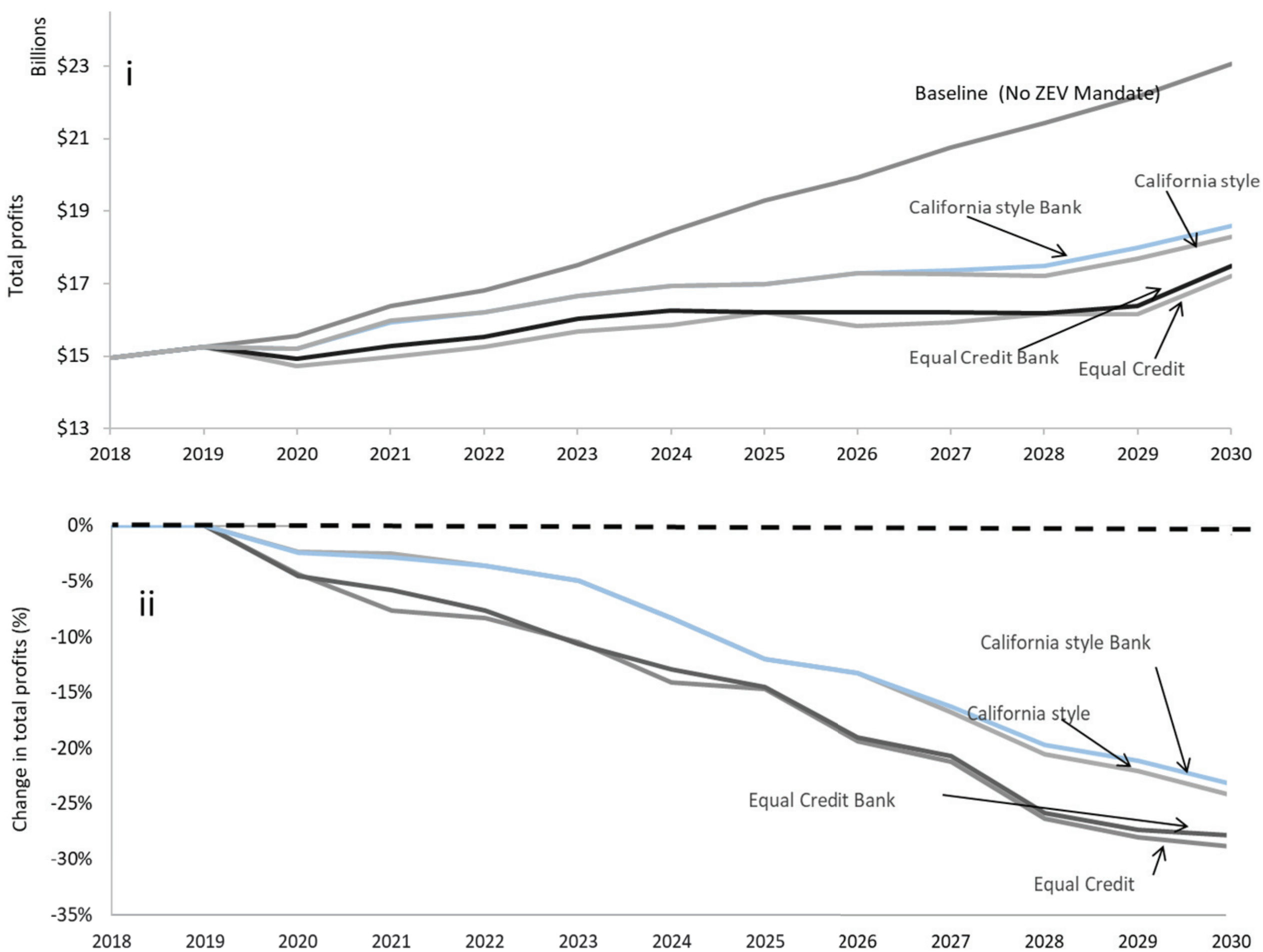

Fig. 4.8 Percentage and total change in automaker industry profits relative to the Baseline under the ZEV Equal credit scenario (with and without Banking) and California style scenario (with and without Banking) (all scenarios are with same ZEV penalty of $10k/credit). All values in Canadian dollars.

Fig. 4.9 depicts the change in consumer surplus (compared to Baseline) over time under the ZEV Equal Credit and California style scenarios. The ZEV penalty for both credit scenarios is $10k/credit. The policy impact on consumer surplus under the California style scenario is consistently lower than the Equal Credit scenario. Thus, if we consider only private costs, both consumers and automakers are better off under California-style credit scenario.

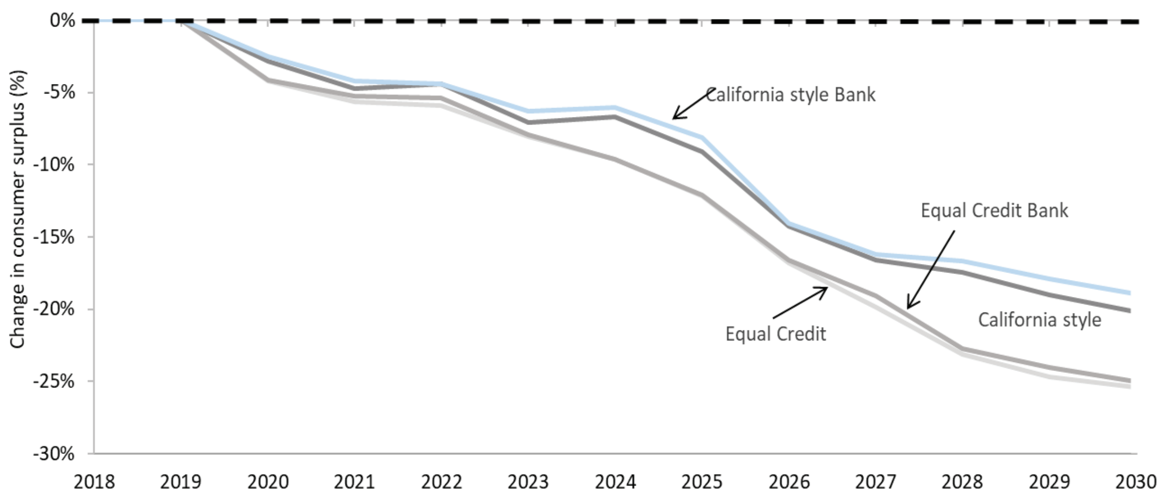

Fig. 4.9 Percentage change in consumer surplus relative to the Baseline under the ZEV Equal Credit scenario (with and without Banking) and California style scenario (with and without Banking) (all scenarios are with same ZEV penalty of $10k/credit)

4.3.3. The impacts of ZEV credit banking

If automakers are allowed to bank credits, they are likely to over-comply with the ZEV credits requirement in the initial years. This effect can be seen in Fig. 4.6 above, which depicts the change in ZEV new market share under the Equal Credit scenario (with $10k penalty/ credit) with and without banking. It may be observed that the new vehicle market share exceeds the ZEV credit requirement when banking is allowed. This effect may be explained as follows. The ZEV credit requirement, as assumed in this study, increases exponentially (5% in 2020, 15% in 2025 and 30% in 2030), making it more difficult to comply in the later years. Arguably, factors such as the decline in battery costs or increase in public charging stations can potentially somewhat make it easier to comply in later years. However, the rates of change of these factors as assumed in this study are relatively slower compared to the exponential increase in the ZEV credit requirement. Resultantly, it is more profitable for the automakers to over-comply in the initial years and use the banked credits to meet part of the requirement in later years. Historical evidence informs that automakers over complied with ZEV regulation in California in the initial years. As noted in the CARB midterm review (CARB, 2017), the number of credits for PHEVs and BEVs earned were about 100,000 more than required in 2013 and 2014, and about 150,000 higher than required in 2015. This finding is similar to the automaker behavior estimated by our model.

Additionally, the effect of banking on PEV composition, automaker profits and consumer surplus are depicted in Fig. 4.7, Fig. 4.8 and Fig. 4.9 is respectively small. While the effect of banking on PEV composition is negligible (Fig. 4.7), it has a mildly positive impact (~1% in 2030) on automaker profits (Fig. 4.8) and consumer surplus (Fig. 4.9).

4.3.4. Sensitivity analysis

To better understand the sensitivity of these results, we use single value deterministic sensitivity analysis to explore how variations in seven key input parameters affect the resulting ZEV new market share (Fig. 4.10), consumer surplus (Fig. 4.11), and automaker profits (Fig. 4.12) in 2030. As an illustrative case we present the three sensitivity results for the ZEV mandate policy with $10k penalty per credit, under the Equal Credit scheme and without any banking of credits (i.e 10k penalty scenario).

First, Fig. 4.10 depicts the degree of sensitivity of the 2030 PEV market share results in the ZEV mandate scenarios to each key input parameter variation, ordered from largest to smallest impact. The 2030 results are most sensitive to consumer preferences. Similar to other modelling studies (e.g., Axsen and Wolinetz, 2018), our results also indicate that recharging access, battery costs and model variety are other important factors that explain the variation in results. Second, the uncertainty in consumer surplus, resulting primarily from variations in battery costs, consumer preferences, price elasticity, and discount rate is depicted in Fig. 4.11. Third, there is large uncertainty in profit estimates, depending on critical parameters such as battery costs, consumer preferences, price elasticity, but automaker profits are not too sensitive to model variety, recharging access, and fuel price, as depicted in Fig. 4.12.

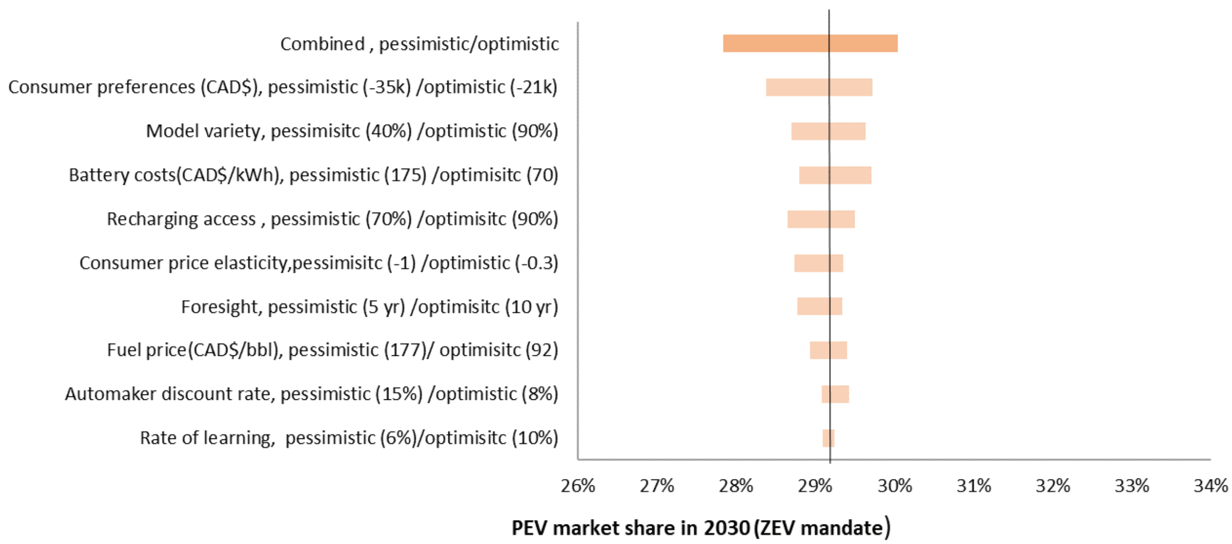

Fig. 4.10 Sensitivity analysis of PEV new market share in the ZEV mandate scenario in 2030 ($10k penalty; Equal credit; No banking).

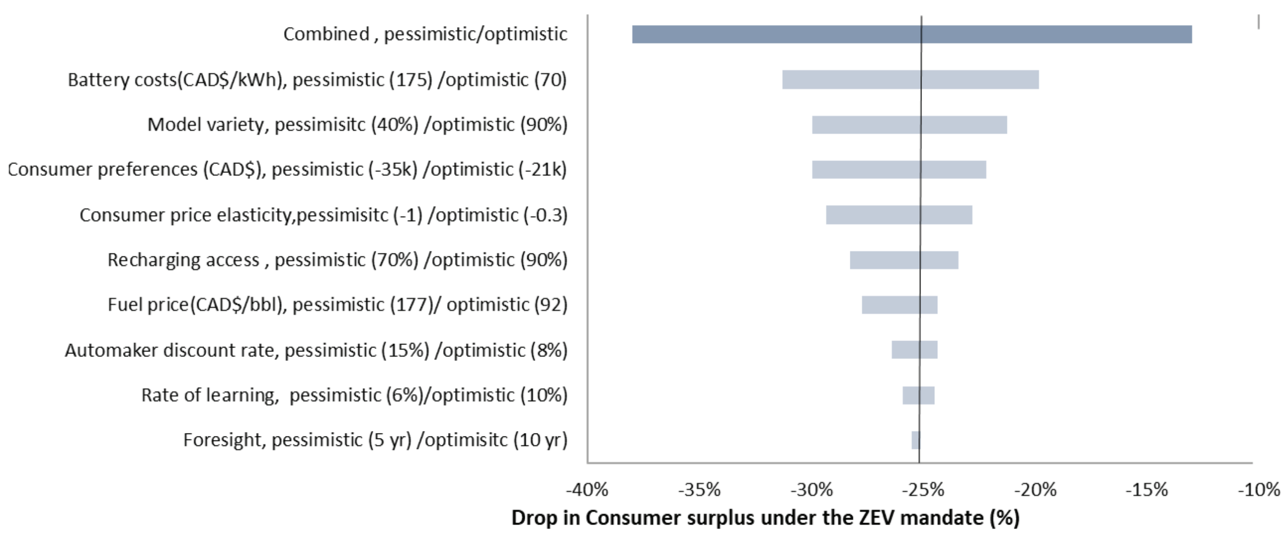

Fig. 4.11 Sensitivity analysis of the change in consumer surplus under the ZEV mandate in 2030 ($10k penalty; Equal credit; No banking)

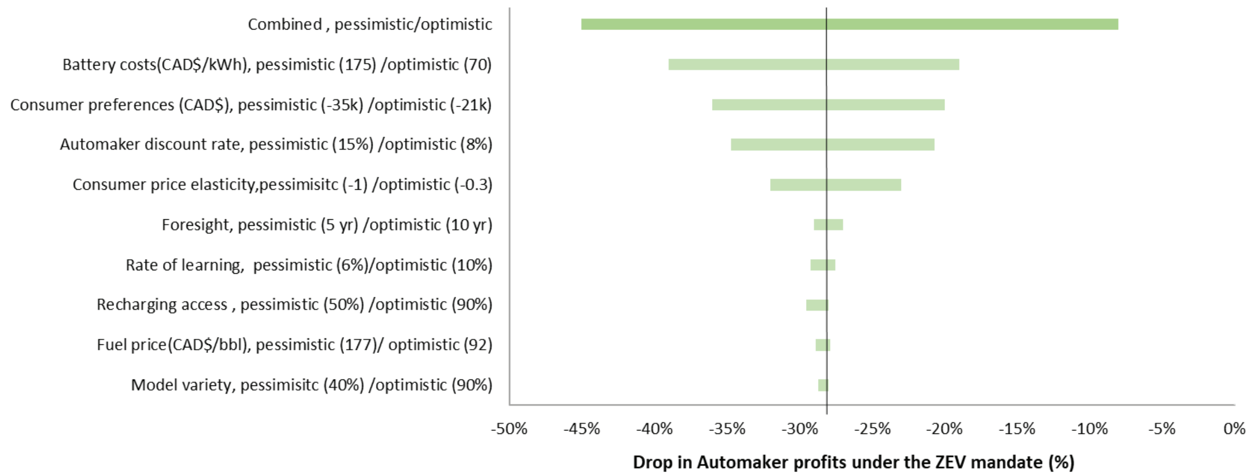

Fig. 4.12 Sensitivity analysis of the change in automaker profits under the ZEV mandate in 2030 ($10k penalty; Equal credit; No banking).

4.4. Conclusion and Policy Implications

In this paper, we examine ZEV mandate policy design and its effects on long term ZEV market share and automaker profits in Canada (2018-2030). We examine whether or not the implementation of the ZEV mandate policy will help achieve the government target of 30% new plug-in electric vehicle market share in Canada. Moreover, we compare the effects of two ZEV mandate credit schemes - California style credit scheme (multiple credits per BEV) and an Equal credit scheme (one credit across all ZEVs), as well as the effect of banking credits.

To address the objectives, we use a technology adoption model (AUM), with an explicit representation of both consumers and an automaker agent (the latter being at the aggregate level). The incorporation of automaker perspective in technology adoption models for climate policy analysis (specifically for the ZEV mandate) has rarely been attempted in literature (Wolinetz and Axsen, 2018). The AUM model also contains some smaller methodological improvements, such as multi-year foresight, including decisions about ZEV model variety, R&D investment, and pricing. Further, our application of the model is itself novel, which relates to examining the effect of ZEV policy design features (i.e. penalty, banking and credit scheme) on new vehicle market share, automaker profits and consumer surplus.

From our analysis, we find that the design of the ZEV mandate could have a significant effect on the policy's ability to achieve 30% new market share for ZEVs by

2030 set by the government. First, we examine the effect of ZEV penalty on market share, finding that a change in ZEV penalty has a significant effect on ZEV new market share. We learn that a high penalty ZEV mandate (~$ 10k/credit) may be required to achieve the government target of 30% plug-in electric market share by 2030. We also model the effect of ZEV penalty on two other outcome indicators, consumer surplus and automaker profitability, to find the following. Increasing the ZEV penalty negatively affects the automaker profits. When compared to the Baseline scenario, the drop in profits in the median case was ~ 10% for a $2.5k ZEV penalty and 28% for a $10k ZEV penalty for the year 2030. Similarly, relative to the Baseline scenario, the drop in consumer surplus in the median case was ~12% for a $2.5k ZEV penalty and 25% for a $10k ZEV penalty for the year 2030.

Second, we examine the variation in total ZEV new market, automaker profitability and the composition of ZEVs under two different credit schemes (California style and Equal credit), finding that the nature of the credit scheme has a notable effect on ZEV composition. While the total ZEV market share is higher under an Equal credit scheme, the proportion of BEVs in the total ZEV mix is higher under the California style credit scheme. These twin results highlight a policy trade-off. While the total ZEV market share is higher in the Equal-credit scheme; it is largely dominated by plug-in hybrid vehicles for a large part of the modelling horizon. Plug in hybrid vehicles do not guarantee a reduction in GHG emissions over the long term as people buying these vehicles could continue to use the vehicles in gasoline mode (Plotz et al, 2017). Thus, while the Equal-credit scheme leads to overall higher ZEV share, it may not lead to desired level of emissions reduction. On the other hand, the California style scheme potentially achieves lower ZEV shares in total (5% lower) but ensures more battery electric vehicles (with zero tail-pipe emissions) on the road. The implication is that an Equal credits scheme may be preferable for increasing the total new ZEV market share while California style scheme is likely to cause a higher percentage of BEVs in the total ZEV mix. Change of credit scheme also has a noticeable effect on profits with drop in automaker profits higher under the Equal credits scheme.

Third, we examine the effect of allowing automakers to bank ZEV credits over time. We find that the banking allowance has a small positive impact on automaker profits and consumer surplus. However, the effect on ZEV new market share is more pronounced. Automakers are likely to over-comply with the ZEV credits requirement in the initial years if banking of credits is allowed.

Of course, our model has limitations. We acknowledge that the absence of empirical data for several key parameters may limit the validity of our assertions. Other limitations include: We model just one aggregate automaker in our model and acknowledge that this can be improved by adding multiple manufacturers and including competition (and sales of ZEV credits) between them. Future research may also incorporate the role of fuel suppliers more explicitly (oil and biofuel refiners and electric utilities). Additionally, automotive industry research investment data is difficult to find and we have had to rely on grey literature and estimates to populate the model.

Despite these limitations, we believe our results generate some policy relevant insights. First, a ZEV mandate can potentially provide a strong push to automakers to increase the supply of plug-in electric vehicles and significantly increase market share compared to a no-ZEV policy scenario. Second, the success of a ZEV mandate highly depends on the design of the policy – especially the level of penalty for non-compliance. The choice of credit scheme can also influence policy outcomes, including overall compliance and the relative sales of different drivetrains. On this last point, policymakers may closely examine the trade-off between a higher total ZEV market share (Equal credit scheme) versus a higher BEV proportion of sales (but lower overall ZEV market share) under the existing California scheme, in order to arrive at a suitable policy for another context.

Chapter 5. Which "second-best" climate policies are best? Simulating cost-effective policy mixes for passenger vehicles[6]

Abstract

In the real-world of political opposition and complex market failures, carbon pricing alone will not achieve deep GHG mitigation targets. Hence, we search for the most cost-effective "second-best" policies. Focusing on the light-duty vehicle sector in the case of Canada, we compare several policies in terms of effectiveness (regarding 2030 GHG goals) and mitigation costs, namely: (i) a carbon tax; (ii) a vehicle emission standard (or VES); (iii) a zero emissions vehicle (ZEV) mandate, and (iv) combinations of all three at various stringencies. In this effort, we apply the AUtomaker-consumer model (AUM), which endogenously simulates consumer and automaker decisions and technological change. Comparing individual policies, the regulations are about three times more expensive than the carbon tax. Among "second-best" policies, the VES is cheaper than a ZEV mandate at lower stringencies, but at higher stringencies the two are similarly efficient (both incentivize widespread ZEV deployment). In policy mixes, cost-effectiveness is improved by a carbon tax. Specifically, inclusion of a $100-150/tonne tax can achieve targets while being 30% to 50% less costly than a regulation alone. We suggest that policymakers implement carbon pricing as stringently as politically feasible (for efficiency), complemented by regulations as needed (for efficacy) to meet GHG targets.

[6] This paper is currently under review in *Ecological Economics*. Drs. Axsen, and McCollum, helped in the writing (review and editing) of this paper, as well as guided me during the conceptual design stage.

5.1 Introduction

Strong policy is needed to meet deep GHG reduction goals globally, and the transport sector is no exception (Cruetzig et al., 2015; Axsen et al., 2020). Real-world experience and various theories indicate that in most cases, a policy-mix is likely needed to achieve GHG goals, rather than a single policy instrument (Sperling and Eggert, 2014; Bhardwaj et al., 2020). The design of such policy mixes ought to consider GHG mitigation effectiveness, as well as cost-effectiveness, political acceptability and transformative signaling (Bhardwaj et al., 2020). In this paper, we explore the impacts and tradeoffs in effectiveness and efficiency for individual policies and a variety of policy mixes.

Regulations and policy-mixes are often considered to be “second-best”, as they lack the efficiency and technology-neutrality of a carbon pricing approach (Bennear and Stavins, 2007; Kahkul et al, 2013). However, in the real-world it is generally accepted that carbon pricing alone will not achieve deep GHG mitigation targets, and that a policy mix is needed (Stiglitz et al, 2017; Kern et al, 2019). One reason is political acceptability, where surveys continually find that carbon and road pricing are much more opposed than regulations, incentives or other climate policies (Rhodes et al, 2017; Douenne and Fabre, 2020; Long et al., 2021). Another broad rationale for a “second best” approach is that carbon pricing alone might not be effective when multiple market failures exist. That is, it is not just the environmental externality of GHG emissions that prevents widespread adoption of low-carbon technologies, but also research & development spillovers and undue market power among suppliers (Bennear and Stavins, 2007; Lipsey and Lancaster, 1956). However, despite the importance and seeming inevitability of such “second best” policy mixes, there is surprisingly little research that systematically compares the impacts of different regulations individually and in combinations.

One important challenge in such research is the need to anticipate and simulate technological change (Stern et 2006; Ma and Nakamori, 2009; Nordhaus, 2014). A regulation tends to be more technology-specific than a carbon price, where the long-term effects can be highly uncertain. Some researchers argue that carbon pricing may be too neutral, as muted price signal may be insufficient to break the lock-in of incumbent technologies or to induce the required near-term upscaling of technologies that will be needed in the longer term. These researchers instead recommend the use of technology-specific regulations to more quickly induce learning-by-doing and other technological change effects (Azar and Sanden, 2011; Kalkuhl et al, 2013; McLaren and Markusson, 2020). That said, regulations are typically found to be costlier than pricing alone (Fox et al., 2017; Jenn et al, 2018; Nordhaus, 2011; Dimanchev and Knittel, 2020), though results are highly sensitive to modeling assumptions. Research in this area needs to carefully consider and represent the endogenous impacts of policy on technological change, in order to better anticipate policy costs.

Another key confusion is that the literature often compares policy categories more broadly, e.g., tax versus regulation, while effectiveness and efficiency can both vary depending on policy stringency (Pahle et al, 2018). On the one hand, more stringent policies seem likely to experience higher overall costs, as low-cost responses or compliance options become exhausted – leading to an increasing mitigation cost curve (Carley et al, 2018; Pahle et al, 2018). On the other hand, some forces of technological change suggest that a stronger or more focused regulation might induce learning curves and technological change more quickly, which in some cases can decrease policy costs over the longer term (Fox et al. 2017). It is thus important for policy analysis to consider a broad range of policy stringencies, individually and in combinations within a policy mix.

With these consideration in mind, our analysis applies the AUtomaker-consumer Model (AUM), which endogenously represents technological change and adoption through the interaction of supply-side and demand-side response to climate policy within the light-duty vehicle sector (Bhardwaj et a., 2021). We examine the effectiveness and cost-effectiveness of climate policies by type (tax versus regulations with differing specificity), by stringency, and individually versus in combination. We consider two types of a regulations: i) a zero-emissions vehicle (ZEV) mandate that requires an increase of ZEV sales, and ii) a vehicle emissions standard (VES) that requires reductions in the average carbon intensity of vehicles sold.

5.1.1 Literature on climate policy cost-effectiveness

A variety of models have been used to quantitatively estimate policy cost effectiveness. Examples include general equilibrium models that simulate interactions across an entire economy (Kalkuhl et al., 2013; Acemoglu et al, 2016; Dimanchev and Knittel, 2020), partial-equilibrium energy-economy models (Small, 2012), and technology adoption or diffusion models which focus on how a specific technology gets adopted over time (Fox et al, 2017; Lam and Mercure, 2021). For any model that is simulating the effects and costs of policies multiple years into the future, it is important to consider the treatment of technological change.

Representing technological change includes concepts such as learning by doing, learning by searching and dynamic consumer preferences (Nordhaus, 2014; Pizer and Popp, 2008). Learning by doing simulates technology learning in terms of how production costs of alternative technology (e.g., electric vehicles) change over time, as a function of increased manufacturing experience (Loschel, 2002). Learning by searching attempts to capture the endogenous decline in production costs as a result of research and development (R&D) activities (Barreto and Kypreos, 2004). Another key component of technological change is the learning that happens on the consumer side. Consumers' preferences for novel, alternative technologies can improve over time as more and more consumers adopt the technology due to the "neighbour-effect" (Axsen et al, 2009). Increased adoption at consumers' end can in turn trigger increased learning (both by doing and searching) on the producer side. Arguably, given the importance of the dynamic interactions between producers and consumers, technological change can be better simulated through explicit representation of both the supply-side and consumer side in a model used to estimate policy cost-effectiveness.

Representing the supply-side perspective and the corresponding technology learning can be particularly important when considering regulations that are directly put onto automakers, such as a vehicle emission standard (VES) or zero emissions vehicle (ZEV) sales mandate. In such policies, automakers have multiple options for compliance, such as investing in new technology, increasing ZEV model variety, changing prices via internal cross-price subsidies, or non-compliance and paying the fine (Bhardwaj et al., 2021). Some supply focused models represent automaker decision making endogenously and often in great detail with multiple automakers, and are rich in technological details regarding vehicle technology types, and vehicle classes (e.g., Michalek et al., 2004; Whitefoot et al., 2017; Jenn et al, 2019). However, as Xie and Lin (2017) point out, most of these models do not represent consumer behaviour in detail, ignoring features such as multiple consumer segments, as well as dynamic consumer preferences.

On the other hand, consumer-focused models have their strengths in representing the demand-side, such as representing heterogeneity through multiple market segments and including various non-monetary factors (such as risk, refuelling infrastructure, and range anxiety) (e.g., Small, 2012; Fox et al, 2017; Lam and Mercure, 2021). Also, such models tend to represent consumer learning, including dynamic consumer preferences (e.g., Small, 2012; Fox et al, 2017; Lam and Mercure, 2021). However, most of these models do not explicitly represent the automaker response to policies (Fox et al., 2017; Lam and Mercure, 2021), limiting their ability to accurately capture the producer-consumer dynamics, as well as endogenous learning effects on the automakers' end. In short, there is a lack of modelling studies in the literature that simultaneously capture technological change at both the consumer and producer end.

Moving on to the specific research questions addressed in this paper, much of this climate policy cost literature has focused on comparing costs by policy type, or technology-specificity (e.g., Fox et al, 2017, Small, 2012). A common finding is that regulations are substantially more expensive than carbon pricing. Comparing the ZEV mandate and the carbon tax, Fox et al (2017) find the mandate to be between 2 to 3 times costlier than the tax. Similarly, Small (2012) finds the VES to be at least 1.5 times costlier than the tax. In stark contrast, Lam and Mercure (2021) find the VES and the ZEV mandate to be an order of magnitude cheaper than the fuel tax. One reason for this difference may be that the examined regulations are of particularly low stringency. Further, Lam and Mercure (2021) observe that the regulations they simulate are more effectively able to address infrastructure failures within the transport sector, contributing to their lower costs. Since they use a model with a strong path-dependence structure (e.g., partly captured by a high rate of change of consumer preferences), progressively higher rates of consumer adoption lead to negative regulation policy costs in later years, offsetting most of the costs in the initial years.

An important omission in cost-effectiveness literature is that most studies focus on the comparison of individual policies (or sometimes policy pairs), and few studies systematically simulate the cost-effectiveness of policy mixes. As examples, Acemoglu et al (2016) compare the welfare effects of a carbon tax and research subsidies for renewables. Similarly, Kalkuhl et al (2013) compare cost effectiveness of individual policies like technology quotas, feed-in tariffs, and taxes. Two studies consider several modelling scenarios with policy pairs. First, Small (2012) finds a policy pair (VES and a tax) to be more cost-effective than the VES alone. Dimanchev and Knittel (2020) compare alternative combinations of a tax and a VES, similarly finding that the policy pair is more cost-effective than the regulation but less cost-effective than a tax alone. In a notable exception to the stream of studies examining policies in isolation or pairs, Lam and Mercure (2021) analyse the cost-effectiveness of multiple policy mixes arising from combining six common policy instruments (fuel tax, registration tax, vehicle tax, ZEV mandate, VES, and ZEV purchase subsidies). They find that the costs of combinations containing ZEV mandates are typically lower than the average costs of constituent policies. Arguably, with implementation of multiple policies being a political reality, academic literature needs to direct more research into examining cost-effectiveness of mixes consisting of multiple policy instruments.

A final gap in the transport literature is that earlier studies have put little emphasis on how cost-effectiveness varies with policy stringency. In most modelling studies, only one or two stringencies are simulated, often with seemingly arbitrary values. Of the few explorations of multiple stringencies, there is considerable variety in the modelled relationship. Small (2012) considers two stringencies per policy and finds that policy costs ($/tonne) are higher for both a higher stringency fuel tax and a higher stringency VES (compared to lower stringency versions). In contrast, Fox et al (2017) test three different stringencies of a carbon tax and ZEV mandate (though with relatively narrow ranges), finding that both can lead to lower costs ($/tonne) with higher stringencies, due to increasing returns to adoption (learning by doing and consumer preference change). Dimanchev and Knittel (2020) compare alternative combinations of a tax and a VES, finding that increasing tax stringency improves the cost-effectiveness of the combination. More research is needed to identify a clear relationship between cost-effectiveness and policy stringency, particularly for the case of regulations and policy mixes.

In short, we identify three main gaps in the transport modelling literature regarding policy cost-effectiveness. Previous modelling studies provide scope for improvement in the treatment of technological change, with most studies lacking a simultaneous representation of dynamic consumer preferences, as well as technological detail, learning by doing, and learning by searching at the automaker's end. Second, most of the above studies lack an examination of policy mixes containing multiple policy instruments, focussing instead on policies in isolation or in pairs. Further, literature has generally ignored an exploration of how policy cost-effectiveness varies with policy stringency. In particular, our understanding of the cost-effectiveness policy stringency relationship is incomplete for the case of regulations and policy mixes.

5.1.2 Current study

We attempt to bridge the gaps identified above. First, we use a technology adoption model, the AUtomaker consumer Model (AUM), which simulates interactions between behaviourally-realistic consumers and a profit maximizing automaker. AUM represents consumer behaviour (heterogeneity and non-financial factors) and dynamic consumer preferences, and incorporates dynamic automaker learning (learning by doing and learning by searching, including feedbacks). In addition, AUM endogenously represents multi-year foresight for the automaker, including decisions about: (i) increasing ZEV model variety, (ii) intra-firm cross-price subsidies, (ii) charger deployment, and (iv) investing in R&D to reduce future ZEV costs.

Second, our policy scenarios are designed to systematically examine the cost-effectiveness of individual policies as well as policy mixes. Most regions plan to employ a suite of policies to achieve (and potentially exceed) their 2030 GHG policy goals. Using our case study as one example, Canada has set a target of 40% reduction in GHG emissions from 2005 levels by 2030, and it hopes to achieve this by putting in place a multi-policy framework (Government of Canada, 2021), including a pricing mechanism and various regulations for the light-duty vehicle sector. We examine multiple stringencies and combinations of light-duty vehicle sector focused policies in Canada to explore the costs of different policy approaches.

Relatedly, we compare the total costs ($) and cost-effectiveness ($/tonne) of alternative policy combinations. For most regions, including Canada, the above GHG targets for 2030 are interim targets towards a longer-term goal of near zero emissions by 2050 economy-wide. This dual objective offers a policy tradeoff between choosing, 1) the cheapest policy mix that meets 2030 targets; and 2) cheapest mix per tonne reduced (even if it exceeds the target and has higher total costs) which is potentially cheaper over the long term. Comparing total costs and cost-effectiveness allows us to comment on the relative merits of each option.

Third, we analyse multiple stringency levels of individual policies and policy mixes to identify the nature of relationship between policy stringency and its cost-effectiveness. This analysis allows us to depict tradeoffs between effectiveness (GHG mitigation) and cost-effectiveness ($/tonne abated). In particular, we focus our attention on regulations, where we discover several different relationships between policy cost-effectiveness and stringency (in some cases non-linear).

Specifically, our research objectives are:

i. Compare emissions reductions (in tonne CO_2e) and costs (in $/tonne of CO_2e reduced) for three common climate transport policies (Zero Emission Vehicle mandate, carbon tax and Vehicle Emission standard) acting individually
ii. Compare emissions reductions (in tonne CO_2e) and costs (in $/tonne of CO_2e reduced) under different combinations of the three climate transport policies (Zero Emission Vehicle mandate, carbon tax and Vehicle Emission standard)

The organization of the paper is as follows: Section 5.2 provides the details of the model used to conduct this study as well as describes the scenarios used to analyse results. Section 5.3 presents the results. Section 5.4 concludes and discusses policy implications of the results.

5.2 Model

To avoid repetition, I do not include Sections 5.2.1, and 5.2.2 here (which were originally part of the paper submitted to Ecological Economics). These sections are essentially the abridged versions of the consumer and automaker component descriptions already presented in chapter 3.

For the current study, I do however make two changes to the model. First, I add a fourth endogenous compliance mechanism to my model. Thus, now apart from the three endogenous automaker compliance mechanisms already included– i.e. (i) increasing ZEV model variety, (ii) intra-firm cross-price subsidies, and (ii) investing in R&D to reduce future ZEV costs, the automaker can comply using a fourth compliance mechanism: charger deployment. That is, the automaker can endogenously contribute to the exogenously increasing electric charging stations. The corresponding equation is in the SI section. Second, I upgrade the model to be able to estimate GHG impacts of a policy (and thus estimate cost-effectiveness). This is described next in section 5.2.3.

5.2.3 Calculating policy costs ($/tonne)

In our model, the cumulative policy cost is the sum of change in consumer surplus and the change in profits under a policy scenario, relative to a reference scenario. The net change in consumer surplus (CS) in policy scenario ('1') relative to the No Policy scenario ('0') is given as:

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

Where U_i= utility of technology 'i' as in equation (1), and β_{PP} is the coefficient of purchase price. Similarly, the change in profits (equation 4, in Section 3.2.2 in chapter 3) can be summed to give the total costs (private) 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
- 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.
- Amenity loss represents 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 PEVs with associated range anxiety.

The consumer surplus and profit calculations consist only of the private policy costs. Thus, unlike Greene et al (2014), we do not include wider social benefits or co-benefits, such as the health benefits from reduced GHG emissions or local air pollution in this analysis. Note that the revenue earned from the tax is also not included as part of the cost calculations presented here, to allow a more direct efficiency comparison. Small (2012) argues that the efficiency of a tax can be considerably influenced by how revenues are used in the economy. We assume revenues are simply a transfer within the economy. Although not included in the results, we found that inclusion of revenues led to negative costs for the taxes.

To calculate policy cost-effectiveness, we also need to estimate the GHG reductions resulting due to each policy. We calculate cost-effectiveness ($/ tonne) as the ratio between the net present value of total policy costs (sum of change in consumer surplus + change in profits) and reduced tonnes of WTW GHG reductions over the forecast period. For estimating GHG emissions, we simulate the total stock of vehicles, their usage per year (vehicle km travelled), and the carbon intensity of travel, each of which we discuss next.

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

$$\sum_{k=1}^{N} S_{t+1,k} = \sum_{k=1}^{N} S_{t,k}\,(1\text{-}d_{t,k}) + \sum_{k=1}^{N} Q_{t,k} \qquad (2)$$

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 3.2 (chapter 3). The vehicle use under policy (V_p) is a function of the projected travel demand in the reference no policy case (V_0), the elasticity parameter (e), and the changes to the fuel cost in the policy scenario relative to the reference case, given by

$$V_p = V_0 \left(\frac{fuel\ cost_P}{fuel\ cost_0}\right)^e \qquad (3)$$

Where $fuel\ cost_P$ is the fuel cost under policy, while $fuel\ cost_0$ is the fuel cost in the reference no policy case. The reference case vehicle use (V_0) in Canada is assumed to be 16000 km a year (Statistics Canada, 2020).

Once the vehicle stock and vehicle use values are known, the total GHG emissions can be obtained by multiplying the product of vehicle stock and vehicle use values with the energy consumption per vehicle and fuel carbon intensity. The vehicle energy intensity for each drivetrain is set exogenously for each drivetrain based on U.S. EIA (2020) and National Energy Board (2019) estimates, and are shown in Table 5.1. For PHEVs, we assume that consumers use electricity to run the PHEVs 70% of the time and use gasoline for the remaining 30% -- which translates to a 70% “utility factor”. Plotz et al. (2021) calculate this utility factor from real world driving data across several countries, and find that utility factor varies with the electric range, and across countries (e.g., for a 100km electric range PHEV, utility was about 70% in Canada and Norway, but only 40% in China and Netherlands). To account for uncertainty, we assume the utility factor is 50% in the pessimistic case, and 90% in the optimistic case – however, in each scenarios the split is exogenous and does not respond to changes in fuel or electricity prices.

Table 5.1 also summarizes our exogenous assumptions about the well-to-wheel (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

(National Energy Board, 2019; EIA, 2020). Carbon intensity remains constant for gasoline in the no policy case, but decreases over time under the effect of the low carbon fuel standard, about to be imposed by the national government (Government of Canada, 2021). 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 (National Energy Board, 2019).

Table 5.1 Vehicle energy intensity and fuel carbon intensity (Canadian) assumptions

Vehicle energy intensity	**2020**	**2030**	**Source**
Conventional (L/100km)	7.55	5.73	National Energy Board (2019), EIA (2020)
PHEV (L/100 km: 30% Gasoline)	2.2	1.63	National Energy Board (2019); EIA (2020)
PHEV (kWh/100 km: 70% electric)	0.13	0.10	National Energy Board (2019); EIA (2020)
BEV-320 (kWh/100 km)	0.19	0.16	National Energy Board (2019)
Carbon intensity (gCO2/MJ)			
Gasoline (Default)	88.1	88.1	National Energy Board (2019); GHGGenius
Gasoline (with Low Carbon Fuel Standard)	88.1	76	Government of Canada (2021)
Electricity	19.5	14	National Energy Board (2019); GHGGenius

5.2.4 Policy scenarios

As a reminder, our case study of Canada has set a target of 40% reduction in GHG emissions from 2005 levels by 2030, and intends to achieve this by putting in place a multi-policy framework (Government of Canada, 2021). GHG emissions from the Canadian light-duty vehicle sector were 85 million tonnes of CO_2e in 2005 (Government of Canada, 2021). The nationwide 40% GHG reduction target translates into an annual target of total GHG emissions of about 52 million tonnes of CO_2e (cut-off used in Fig. 5.2) from the light-duty vehicle sector by 2030. Without any policy, Canada expects its total nationwide GHG emissions to be 815 million tonnes of CO_2e by 2030, with the light-duty vehicle sector contributing about 11%, or 83 million tonnes of CO_2e (Government of Canada, 2021). The total emission reductions (sum of annual reductions between 2020 and 2030) required to meet the 2030 target amounts to 147 million tonnes of CO_2e (the cut-off used in Fig. 5.3 of the results).

We first simulate the impacts of policies in Canada as of Summer 2020 (acknowledging that the policy landscape is changing) – we call this the "Current policy" scenario. This scenario includes a federal carbon tax, starting at $20/tonne CO_2e in 2018 and increasing to $50/ tonne by 2022. In addition, a nationwide VES is effectively in place, due to policy alignment with the U.S, requiring emissions from light-duty vehicles to be less than 100 g CO_2e per km by 2025. Further, at the time of writing of this paper, the federal government is considering the implementation of a Low Carbon Fuel Standard (LCFS) requiring carbon intensity reductions of approximately 15% by 2030 (Government of Canada, 2020). A low carbon fuel standard mandates the fuel suppliers to reduce the carbon intensity (in gCO_2e/MJ) of the fuel supplied. Carbon intensity of fuels can be reduced either by fuel mixing (e.g. mixing ethanol with gasoline) or by lowering life cycle carbon intensity (e.g. carbon capture storage), where the resulting carbon intensity is depicted in Table 5.1.

For our analysis, we depict the current policy context, by simulating light-duty vehicle GHG emissions under three scenarios: (i) "No policy", this assumes no policies are in place; (ii) "Current policy", this scenario assumes that the carbon tax and vehicle emission (fuel economy) standards at the current stringencies at are in place; (iii) "Current + LCFS"- this scenario assumes that a Low Carbon Fuel Standard (LCFS) policy is in place in addition to the current policies described above.

Next, we compare the GHG impacts of the three individual policies; a carbon tax, a VES and a ZEV mandate, with multiple stringencies for each policy. Under the Tax-50 scenario, tax stringency increases by $10/tonne a year from $30/tonne in 2020 until it reaches $50 a tonne in 2022, where it stays constant till 2030. Similarly, for Tax-100, Tax-150, Tax-250, and Tax-350 scenarios, the tax rate gradually increases to $ 100/tonne, $150/tonne, $250/tonne, and $350/tonne respectively in 2030.

The VES sets targets (expressed in gCO_2e/km) for the level of emissions that can be released per km per vehicle. For example, the 'VES-100' scenario requires automakers to improve the fuel economy (and thus reduce the energy requirement per kilometre driven) of the vehicles produced to 100g/km by 2025 (~ 1.3MJ/km or 55 miles per U.S. gallon or alternatively 4.2L/100km), and stays constant at that level until 2030. The VES-100 scenario resembles the stringency of the vehicle emissions standards in place in Canada currently. The VES-120, VES-110, VES-90, VES-80, VES-65, and VES-50 scenarios respectively require emissions to be less than 120g/km, 110g/km, 90g/km, 80g/km, 65g/km, and 50g/km by 2030. The VES-80 scenario resembles the stringency of the vehicle emissions standards set as 2030 target by the European Union. The units 'g/km' are expressed in WLTP (World harmonized Light-duty vehicles Test Procedure) metrics, which are the globally accepted metric for vehicle regulations, and are set to replace the New European Driving Cycle (NEDC) previously being used in Europe (European Union, 2021). The WLTP metric gives a number that is typically 10-20% higher than the NEDC metric.

The ZEV mandate requires manufacturers to make a certain percentage of zero or low emission vehicles for sale. The 'ZEV-30' scenario requirement is 5% in 2020, 15% in 2025 and reaches 30% by 2030. This is similar to the ZEV mandate in place in British Columbia, Canada, as well as the sales goals (but not yet mandated) in Canada federally. The requirements for new market share in 2030 under the ZEV-20, ZEV-40 and ZEV-50 scenarios are 20%, 40% and 50% respectively. In each case, the required sales increase at an annual rate, which varies for each stringency.

As a final step, we simulate policy combinations to identify scenarios that achieve the 2030 GHG targets under the median case assumptions of input parameters. While it is possible to examine many policy combinations, we include four stringencies for each policy, which are more in line with real-world experience of actual and planned stringencies:

- Carbon tax: None, Tax-50, Tax-100, Tax-150
- Vehicle emissions standards: None, VES-100, VES-80, VES-65
- Zero emissions vehicle mandate: None, ZEV-20, ZEV-30, ZEV-40

5.3. Results

In this section we first examine the effects of the individual policy scenarios on reducing GHG emissions out to 2030 and the corresponding costs (Section 5.3.1).

Additionally, we compare the effectiveness and cost-effectiveness of policy combinations in Section 5.3.2.

5.3.1 Current baseline and individual policies

Before examining individual policies, we begin by depicting the GHG emissions under the current policy context. Fig. 5.2A depicts the GHG emissions from Canada's light duty vehicle sector under the three scenarios described above. (i) "No Policy", (ii) "Current Policy", and (iii) "Current Policy + LCFS". The Y-axis represents the annual emissions in million tonnes of CO_2e, with uncertainty bands indicating the range due to pessimistic and optimistic parameter values. As can be seen in Fig. 5.2A, the GHG emissions are simulated to increase under the No policy scenario. In contrast, the emissions fall under the Current policy and Current policy + LCFS scenario, but not enough to meet the 2030 target.

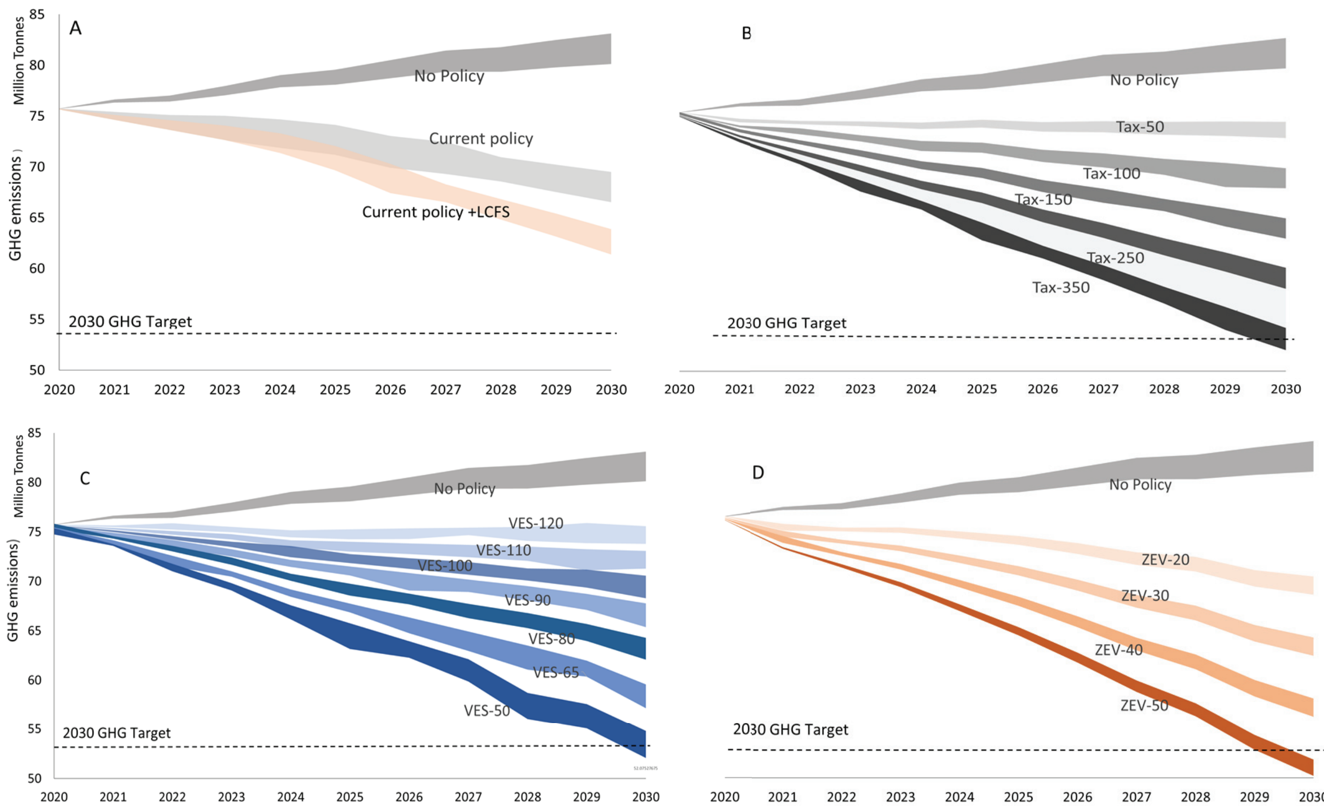

Fig. 5.2. WTW GHG emissions (in million tonnes) to 2030, under different policy scenarios: A= Current (Summer 2020) policy context; B= Tax only; C=VES only; D= ZEV mandate only.

We next examine the effectiveness of individual policies in achieving the 2030 GHG reduction target. First, we consider the case of the carbon tax (Fig. 5.2B). Alternative stringencies of the carbon tax reduce GHG emissions by different amounts, however the stringency required to meet the 2030 target under the median case is about $350/tonne, while the highest stringency currently in place (e.g., $150 per tonne in Sweden) is unlikely to meet the target, acting alone. Next, looking at the VES standards (Fig. 5.2C), 2030 GHG emissions are only moderately decreased (15% compared to No Policy in 2030) for the stringency levels currently in place in most regions (e.g., VES-100 g/km under the WLTP measure). For the VES alone to meet the 2030 target, the emissions requirement per vehicle needs to be 50g/km or lower by 2030. Even at VES-50g/km, the GHG target is met only under optimistic conditions. Finally, for the ZEV mandate, a stringency of 30% new market share for ZEVs (similar to the ZEV mandate in place in British Columbia, Canada) is unlikely to reach the 2030 GHG target. At the stringency of 50% new market share for ZEVs, the policy is able to achieve the 2030 GHG target even under the pessimistic case, acting alone (Fig. 5.2D). In short, we find that within our model, each individual policy could, in theory, be pushed far enough to achieve the 2030 target.

Fig.5.3 depicts the cost-effectiveness results for the individual policies at different stringency levels. As outlined in Section 5.2.3, the cost effectiveness (expressed in $/tonne) is the ratio of total costs (i.e., change in private consumer surplus and profits, relative to the No Policy scenario between 2020 and 2030), and total GHG emissions reduced between 2020 and 2030, thus indicating average costs rather than marginal costs. The grey lines in Fig.3 are centred around each cost effectiveness value and indicate uncertainty due to pessimistic and optimistic values for the input parameters.

The first observation is regarding the relative cost-effectiveness ($/tonne) of the three individual policies. We find the carbon tax to be the most cost-effective policy with costs that range from $ 60 to $230/tonne CO_2e, across all stringencies and pessimistic/optimistic assumptions. While the carbon tax induces some low-carbon vehicle adoption, the bulk of the emissions reductions are attributed to a reduction in vehicle travel demand (VKT). The policy costs indicate the loss in utility and profits and do not include the revenues collected from the tax. The magnitude of tax revenues is greater than the policy costs--thus if tax revenues are included, we would estimate negative costs for all carbon scenarios (all stringencies, and both optimistic and pessimistic assumptions).

In contrast, both regulations are three to four times more expensive than the carbon tax. The VES costs range from $ 440 to 800/tonne. The ZEV mandate costs range from $ 670 to 980/tonne for lower stringencies (ZEV-20 and ZEV-30). Interestingly, the costs of the VES and ZEV mandate are so close at higher stringencies (beyond 80g/km for the VES and beyond 40% for the ZEV mandate) that for practical purposes they are identical.

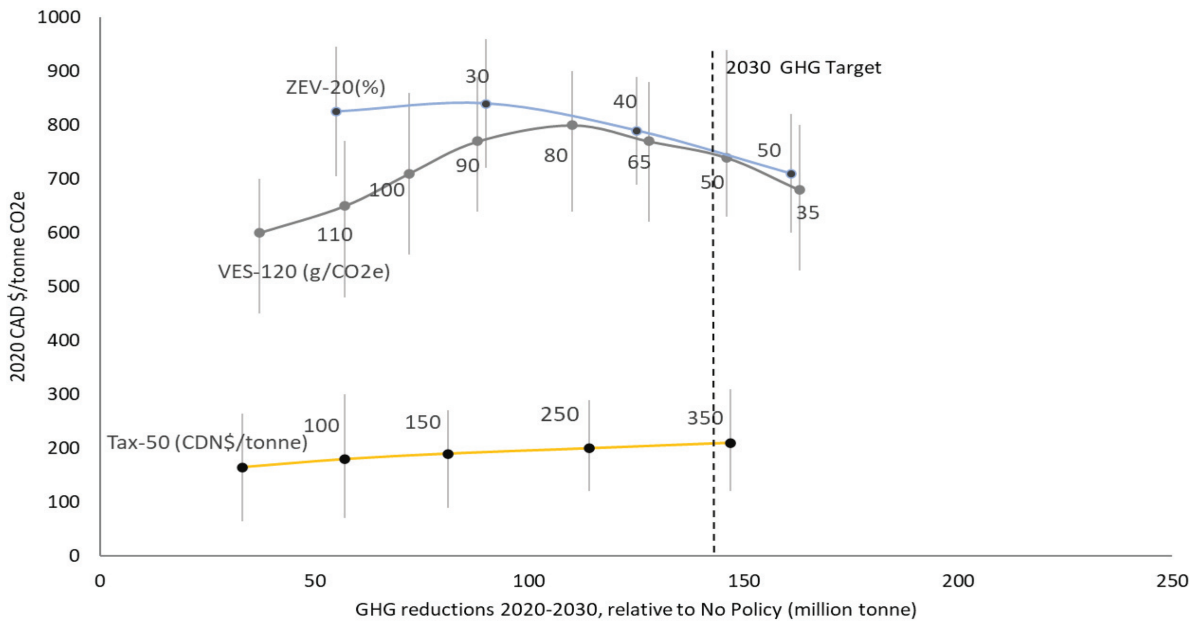

Fig.5.3 Change in the cost effectiveness of individual policies with increasing policy stringency, plotted against the corresponding GHG reductions (X-axis).

Comparing costs across policy stringencies, we see that cost-effectiveness has a complex relationship with policy stringency (Fig. 5.3). For the tax, costs (in $/tonne) increase with increasing stringency, such that a $350/tonne tax is 20% costlier than a $50/tonne tax (with mitigation costs of $34/tonne over $171/tonne, respectively). For the ZEV mandate, a reverse trend is seen compared to the carbon tax, as its costs decline with increasing policy stringency. For example, a 50% ZEV mandate is 17% cheaper than a 30% ZEV mandate (with mitigation costs of $140/tonne lower than $850/tonne, respectively). A more stringent ZEV policy pushes new low-carbon technologies sooner, which causes more substantial low-cost breakthrough, due to learning by doing effects and quicker improvement in consumer preferences. For the VES, increasing stringency displays an inverted U-shaped curve effect on cost-effectiveness. Initially, increasing stringency reduces its cost-effectiveness--a 100 g/km VES is 7% costlier than a 110g/km VES (with mitigation costs of $43/tonne higher than $659/tonne, respectively). This is because the incremental GHG reductions achieved by increasing the stringency of the emissions standards, is lower compared to the corresponding increase in costs caused by the higher stringency. This effect peaks at a median of $798/tonne at a stringency of VES-80g/km. Beyond that, it is cheaper for automakers to comply with VES primarily by selling ZEVs. On further increasing the stringency, the VES acts similar to a ZEV mandate—inducing more investment in and deployment of ZEVs. The cost-effectiveness displays a reverse trend here, where it improves with increasing stringency. A key takeaway is that at higher stringencies, the VES and ZEV mandate can each achieve similar GHG mitigation levels, at similar costs.

5.3.2 Policy combinations

For our second research objective, we present results for the possible policy combinations formed by combining stringencies of the three individual constituent policies. We get a total of 64 policy scenarios, as summarized in Table 5.2. For each policy scenario, we use a (√) to indicate if that scenario achieves the 2030 target under median input parameter assumptions. We group these policy mixes by carbon tax stringency, and within each tax stringency category compare 16 different permutations of VES and ZEV mandate stringencies. With a $50/tonne tax (i.e., Tax-50), six scenarios meet the 2030 GHG reductions target. For the Tax-100 category, eight of the sixteen possible scenarios meet the 2030 GHG reduction target. Under the Tax-150 category, ten scenarios are estimated to meet the 2030 target. As expected, the likelihood of a policy mix meeting the 230 GHG target increases with increasing stringency of constituent polices. We also find that with the policy stringencies and combinations we have selected, four policy mixes are successful without a VES, and four policy mixes are successful without carbon pricing. However, none of our policy mix scenarios were successful without a ZEV mandate (though, such mixes could be successful with higher tax or VES stringencies, as described in the previous section).

Table 5.2 Policy combinations. Tick (√) represents the scenarios that meet (or exceed) the 2030 GHG target for the 'median' value assumptions of the input parameters. 28 combinations meet the target.

Tax-None		ZEV Mandate (%)			
		None	ZEV-20	ZEV-30	ZEV-40
Vehicle Emission Standards (g/km)	None				
	VES-110				√
	VES-100				√
	VES-90				√

Tax-50 ($/tonne)		ZEV Mandate (%)			
		None	ZEV-20	ZEV-30	ZEV-40
Vehicle Emission Standards (g/km)	None				√
	VES-100				√
	VES-80				√
	VES-65				√

Tax- 100 ($/tonne)		ZEV Mandate (%)			
		None	ZEV-20	ZEV-30	ZEV-40
Vehicle Emission Standards (g/km)	None				√
	VES-100			√	√
	VES-80			√	√
	VES-65			√	√

Tax-150 ($/tonne)		ZEV Mandate (%)			
		None	ZEV-20	ZEV-30	ZEV-40
Vehicle Emission Standards (g/km)	None			√	√
	VES-100			√	√
	VES-80			√	√
	VES-65		√	√	√

Note: The 'Tax-150 VES-65 ZEV-None' scenario just misses the 2030 GHG target, hence is not indicated by a tick mark. This is due to the assumptions in the model. In general, a combination of just the VES and Tax could very well mee the GHG target, even without the presence of the ZEV mandate.

Next, we compare the cost-effectiveness of these policy combinations according to increasing policy stringency (Fig. 5.4), plotted against the corresponding GHG reductions (X-axis). In each curve (made of 4 points) VES policy stringency increases from the left to the right (None, VES-100, VES-80, VES-65), with the stringencies of the carbon tax and the ZEV mandate being constant along that particular curve. We plot these curves simply as one way to give a frame of reference to the viewer. The different coloured curves indicate the combinations with the tax level held constant for a particular colour: black (No Tax), grey (Tax-50), blue (Tax-100), and orange (Tax-150).

One key finding is that adding an increasingly stringent carbon tax to a policy mix substantially reduces the costs ($/tonne) of the mix. The costs for policy mixes with carbon tax stringency of $ 50/tonne are on average 25.7% lower than costs for mixes with no tax. For example, the “Tax-None VES-100 ZEV-20” scenario has a median cost of 807 $/tonne—increasing just the tax to $50/tonne reduces the median cost to 603 $/tonne. Similarly, policy mixes with a tax of $100/tonne are on average cost 23% lower than mixes with tax of 50 $/tonne. In line with this trend, the costs for policy mixes with carbon tax stringency of $ 150/tonne are on average 19.8 % lower than costs for mixes with tax of $ 100/tonne.

For the most part, increasing stringency of regulations increases policy costs ($/tonne), all else held constant. Though, these increases are small for the VES (about 10% per incremental increase in stringency), and even smaller for ZEV mandate (about 3% per incremental increase in stringency). For example, the median costs of policy mixes increase by 11% on increasing the VES stringency from VES-100 (e.g., Tax-150 VES-100 ZEV-40) to VES-80– where costs are increased from 357 to 398 $/ tonne. However, when VES stringency is increased further from VES-80 to VES-65, the costs of policy mixes stay constant or decrease a bit – which results from the U-shaped cost curve we identified for the VES when modelled individually (Fig.5.3).

Changes in the ZEV mandate stringency cause a similar effect on policy mix cost-effectiveness. For example, the median costs of policy mixes increase by 3% on increasing the ZEV mandate stringency from 20% to 30% (with $150/tonne tax and no VES). When ZEV stringency is increased further from 30% to 40%, the costs of policy mixes typically decrease a bit, or stay constant.

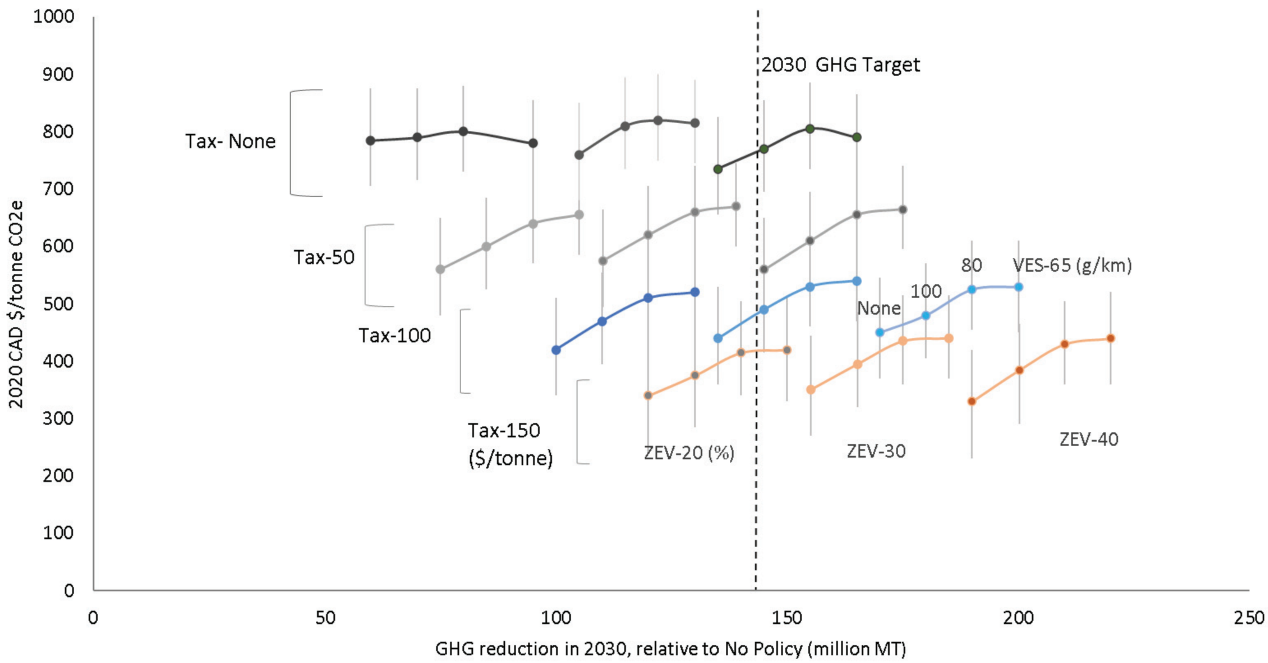

Fig.5.4. Cost effectiveness of alternative policy mixes with increasing policy stringency, plotted against the corresponding GHG reductions (X-axis).

As a final exercise, Fig.5.5 compares the total costs ($) and again cost-effectiveness, $/tonne) of the different policy combinations that achieved the 2030 target (dots to the right of the vertical target line in Fig. 5.4). For comparison, the bottom histograms in Fig. 5.5 depict the costs of stringent individual instruments, as already shown in Fig. 5.3. The simultaneous examination of total costs and costs per tonne abated gives two perspectives: 1) What is the cheapest policy mix that meets 2030 targets? and 2) What mix is cheapest per tonne reduced (even if it exceeds the target and has higher total costs)?

If meeting the 2030 target in the cheapest way is the singular priority, aside from a $350/tonne carbon tax, a policy mix combining a ZEV-30 and Tax-150 (with no VES) presents the cheapest option from the combinations that we simulate. This policy mix costs 52 billion $, which is 43% costlier than a $350/tonne tax, and 57% cheaper than a VES or ZEV mandate acting alone. In terms of cheapest policy mix per tonne reduced, the results change slightly: a combination of ZEV-40 with Tax-150 (no VES) presents the cheapest option. This policy mix leads to costs of $307/tonne, which is 49% more costly than a $350/tonne tax, and 51% cheaper than a VES or ZEV mandate acting alone.

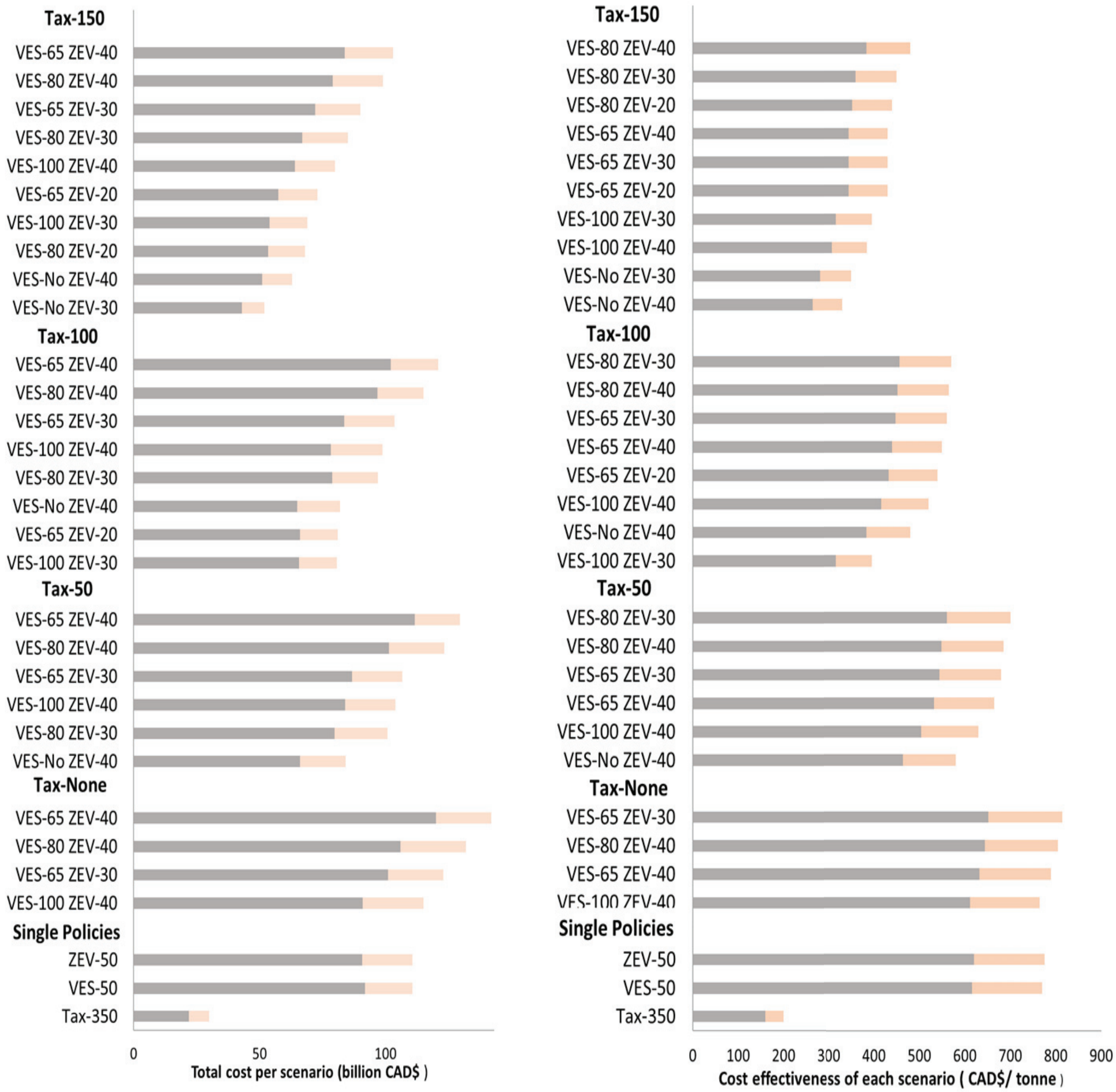

Fig 5.5. Total costs (= drop in automaker profits + drop in consumer surplus) and cost-effectiveness for the 31 scenarios that meet (or exceed) the 2030 GHG target. The 31 scenarios include 28 policy combinations and 3 individual (Tax-350, ZEV-50, and VES-50) policy scenarios. The total cost spit is also indicated. Grey portion is the drop in consumer surplus, while the orange portion depicts the drop in automaker profits. Consumer surplus drop constitutes the bulk (~80%) of costs across scenarios.

One major observation for the policy mix results is that including a tax (as strong as feasible) is key to achieving the target at lowest costs. Secondly, in some cases it seems that including both regulations (VES and ZEV mandate) may increase costs though that depends on the strength of the tax.

5.4. Discussion and conclusions

5.4.1 Key findings

In this paper, we attempt to find cost-effective 'second-best' policies and policy mixes for reducing GHG emissions from the light-duty vehicle sector. While others have compared pricing with regulations, few have systematically compared the cost-effectiveness of multiple regulation, in different policy and stringency combinations.

In this effort, we use a technology adoption model, AUM, which explicitly simulated decision-making on the supply and demand sides. Specifically, AUM represents consumer behaviour (heterogeneity and non-financial factors) and dynamic consumer preferences, and incorporates dynamic automaker learning (learning by doing and learning by searching, including feedbacks). We systematically examine multiple policy scenarios to compare and contrast the cost-effectiveness of individual policies (carbon tax, vehicle emission standard, and zero emission vehicle mandate) and their policy mixes. Further, we explore how policy costs change with changes in policy stringency. In this section we summarize the key cost-effectiveness results, for individual policies and for policy mixes, also discussing how policy costs vary with stringency in each case.

The carbon tax was found to be the most cost-effective single policy, which on average across our simulations is three times cheaper than the two supply-focused regulations. The direction of this results is expected from economic theory (Nordhaus, 2011), and aligns with the observations of existing literature (Small, 2012; Acemoglu et al, 2016; Fox et al, 2017). The magnitude of the cost of the tax in our study ($60 to $200/tonne mitigated) is similar to Fox et al (2017)'s estimate of $180/tonne, and Small's (2012) cost estimate of $75-130/tonne. Regarding variation in cost-effectiveness with stringency, the carbon tax became increasingly costlier ($/tonne) with increasing stringency, a finding observed by Small (2012) as well. Though in terms of magnitude, our results differ. Our analysis shows that a seven times more stringent tax ($350/tonne vs $50/tonne) is only 20% costlier (~$200/tonne vs ~$170/tonne, respectively), while Small (2012) found a more proportional relationship (i.e., a two-times more stringent tax to be two-times costlier).

Our results show that regulations are more expensive (in $/tonne) than taxes, which supports most existing literature (e.g., Fox et al, 2017; Small, 2012, Acemoglu et al, 2016), but differs from Lam and Mercure (2021), who find regulations to be less expensive than taxes. In terms of magnitude of difference, the cost of regulations in our study were about three times higher than taxes, which is similar to some previous estimates (e.g., Fox et al, 2017).

However, more unique to the present study, we found the costs ($/tonne) to vary with stringency. We discover that the VES follows an inverted U-shaped curve-like relationship between cost effectiveness and policy stringency. The VES is cheaper (~$600/tonne) than the ZEV mandate (~$800/tonne) at lower stringencies (e.g., VES-120g/km, VES-110g/km, VES-100g/km). This effect peaks at a median cost of about $800/tonne at a stringency of VES-80g/km. Beyond that, on further increasing the stringency (e.g., VES-65g/km, VES-50g/km), the VES acts similar to a ZEV mandate, and costs decrease (or cost-effectiveness improves) with increasing stringency. Some similar results were found by Fox et al (2017), where stronger technology standards are more cost-effective at higher stringencies due to increasing returns to adoption. Small (2012) found that increasing the stringency of a VES reduces cost-effectiveness. By considering a broader spectrum of policy mixes and stringencies, while also representing numerous aspects of technological changes, our results help to identify the potential complexities and non-linearities in the cost-effectiveness of different types of regulations.

We also examine the relative cost-effectiveness of different combinations of regulations and taxes. Adding a ZEV mandate or a VES to a tax increases policy costs ($/tonne), where such policy mixes are typically 50% costlier (or more) than a tax alone. On the other hand, we find the policy mixes to be cheaper than individual technology standards. Combinations of the ZEV mandate and the VES with the tax were on average 30% (or more) cheaper ($/tonne) than individual regulatory standards. Our results align with Dimanchev and Knittel (2020) and Small (2012), where combinations of tax and a VES were costlier than the tax alone, but cheaper than the VES alone.

Among policy mixes, costs (and cost-effectiveness) also vary according to policy stringencies. Increasing the stringency of the carbon tax in a policy mix substantially reduced the costs of the mix, all else held constant. Each $50/tonne increase in tax stringency, typically leads to a 20% reduction in policy mix costs ($/tonne). The finding that the cost-effectiveness of policy mixes improve with increasing tax stringency is supported by Dimanchev and Knittel (2020). For the most part, increasing stringency of regulations increases policy costs ($/tonne), all else held constant. Each 20% decrease in VES emissions requirement (e.g100 g/km to 80 g/km), typically leads to 10% (or lower) increase in policy mix costs ($/tonne). For the ZEV mandate, each 10-% point increase in policy stringency (e.g., 30% to 40%) increased policy mix costs ($/tonne) by 3% or lower.

5.4.2 Policy implications

We can also draw some region and sector-specific policy insights. Sufficiently stringent individual policies can meet the GHG target, though implementation of individual policies at such high stringency may not be feasible due to political unacceptability (taxes) or very high mitigation costs (ZEV mandate or VES). Policy mixes can be suitable second-best alternatives to taxes.

Among policy mixes, cost-effectiveness can be improved by including a carbon tax. Specifically, inclusion of a $100-150/tonne tax can achieve targets while being 30% to 50% less costly than a regulation alone. We suggest that policymakers implement carbon pricing as stringently as politically feasible (for efficiency), complemented by regulations as needed to meet GHG targets. Secondly. in some cases, it seems that including both regulations (VES and ZEV mandate) may increase policy costs, but in other cases they might be complementary.

5.4.3 Limitations

Our analysis includes numerous limitations that should be acknowledged and considered when interpreting our results, while also pointing the way for future directions to improve this research area. In particular, we identify the numerous challenges and uncertainties associated with modelling technology change, including automaker decisions, the impacts of manufacturing experience and various innovation activities, and consumer response to technology (and price changes) in the present and future. In particular, automotive industry research investment data is difficult to find and we have had to rely on grey literature and estimates to populate the model. We have sought to identify uncertainties in our model explanation, and to represent some degree of uncertainty through our simulations of optimistic, pessimist, and median scenarios. That said, future research should seek to narrow the ranges of these uncertainties, and perhaps also to utilize more sophisticated approaches to uncertainty (such as Monte Carlo analysis, or Bayesian approaches to parameter uncertainty).

Another methodological limitation is that we include just one aggregate automaker in our model, and thus miss insight into the various strategies that might be followed by a range of automakers competing for sales in a given region. For example, Jacobsen (2013) considers seven auto manufacturers and consider competition between firms, using game theory principles. Such resolution could be particularly valuable for research exploring the impacts of the ZEV mandate (and other supply-focused policies) on different automakers, say, incumbent automakers versus new entrants (e.g., Tesla).

Further, our framing of policy cost-effectiveness flows from one perspective of many. Being a partial-equilibrium model focused on one sector, our cost estimates miss out on the wider economic impacts that would be quantified in a general-equilibrium model. Further, we have selected a definition of costs that includes only private costs to consumers and automakers (per GHG tonne abated), thus excluding other potential social or co-benefits (e.g., improvements in health, reduced accidents or reduced local air pollution). Inclusion of such co-benefits would be highly uncertain in magnitude, but would likely decrease the costs of each policy scenario.

Further, our results are unique for our present case study of Canada. Because we use Canada-specific survey data and policies (and frame the magnitude of automaker behaviour around the size of Canada), various response, effectiveness and cost-effectiveness results could be quite different if applied to other regions. For example, we assume a nationwide ZEV mandate implemented uniformly across all regions within the country. Similar policies implemented in another region (say, the US, with the ZEV mandate implemented only in some states but not in others), might yield different impacts, e.g., as found in Jenn et al (2019) and Goulder et al (2012).

Chapter 6. Discussion & Conclusions

The overarching aim of the research work is to help policymakers design suitable policy to reduce GHG emissions in the light-duty vehicle sector. This thesis contributes to this larger objective by addressing two broad categories of challenges in transport climate policy literature (described in Sections 1.2 and 1.3). First, challenges in transport literature related to policy evaluation include: focus that has largely been on one (or two) criteria, lacking a multicriteria evaluation of policies; little research that has examined policy mixes, as well as the resulting interactions between policies; and a lack of research on the effect of policy stringency and design, in particular for supply-side regulations. Second, challenges in transport literature related to modelling include: difficulties in representing realistic consumer behavior features like non-financial factors and heterogeneity; simplistic or non-existent representation of the supply side (namely, automakers) and supplier-focused policies; simplistic representation of technological change.

As a first step towards addressing challenges in policy evaluation, as outlined in chapter 2, I explore reasons for combining multiple policy instruments, and qualitatively assess policy mix interactions on multiple criteria. In chapter 3, I develop a technology adoption model, which simultaneously includes modelling features like consumer behavioral realism, supply-side (automaker) representation, and technological change, in an attempt to partially address challenges related to transport modelling. To address the lack of studies on policy design of supply-focussed policies, I use my model to examine the ZEV mandate policy design effects in chapter 4. Finally, to complement the qualitative investigation of policy mixes initiated in chapter 2, I use my model to quantitatively examine policy mixes and policy stringency in chapter 5. This research work has been able to make some contributions, which are outlined in sections 6.1-6.4, along with the key findings. Finally, I conclude with a summary of policy implications and directions for future research.

6.1 A framework for policy mixes and interactions

While multiple policies are often implemented simultaneously in the real world, the transportation literature has devoted little attention to policy mixes, especially in the light-duty vehicles sector (Lam and Mercure, 2021). There has typically been a lack of investigation into the reasons for why we need multiple policies (if at all), or how might policies interact with each other, and how might we evaluate such policy interactions qualitatively or quantitatively on multiple criteria (Oikonomou and Jepma, 2008; Flanagan et al, 2011). To this end, I review available literature largely from outside of transportation and then use the insights gained to develop a qualitative framework for policy evaluation (e.g., Rogge and Reichardt, 2016; Oikonomou and Jepma, 2008; Howlett and Rayner, 2011). This work takes initial steps to bring the concept of policy mixes and policy interactions more to the forefront of transport policy work, especially for climate policies affecting the light-duty vehicle sector. I believe this acknowledgment of interactions and their complexity can improve the work of transportation researchers, especially quantitative policy modelers, by helping to stimulate reflection on policy interactions beyond just GHG effectiveness and cost-effectiveness, but also impacts on political acceptability and processes of innovation and societal transformation.

Several findings emerge from this study. First, I identify rationales for why the use of policy mixes may be justified. These include- (i) the “three leg” perspective, that different policies should address different sub-sectors of GHG mitigation (e.g., vehicles, fuels, and travel demand) (Creutzig et al, 2011; Sperling and Eggert, 2014), (ii) the “market failure” perspective, that a different policy is needed to correct each market failure (e.g., negative externalities and R&D spillover effects) (Bennear and Stavins, 2007; Lehmann, 2012; Twoney, 2012); (iii) the “political process” perspective, that considers the reality of the present policymaking context, including the political acceptability of policy instruments, (Howlett and Rayner, 2013; Kern et al, 2017); and (iv) the “systems” perspective, that policy needs to send signals to channel innovation and break any lock-in to incumbent technologies and practices (Foxon and Pearson, 2008; Weber and Rohracher, 2012; Rogge and Reichardt, 2016).

Second, building from the reviewed literature and four perspectives, I propose a simple four-criteria qualitative framework to explore and to generate hypotheses regarding interactions between various policies. The four criteria I consider are: (1) effectiveness at GHG mitigation, (2) cost-effectiveness ($ per tonne/CO_2e abated), (3) political acceptability, among citizens and stakeholders, and (4) transformative signal, that is, providing a clear stimulus for various stakeholders to invest and contribute to the transition to one or more low-carbon pathway.

Third, I employ the framework to discuss potential interactions between six climate policies in British Columbia, Canada, which apply to light-duty vehicles: a carbon tax, ZEV purchase incentives, charging infrastructure rollout, a low carbon fuel standard (LCFS), a vehicle emission standard (VES), and a ZEV sales mandate. Based on literature, empirical evidence, and logic, I discuss hypotheses for how each pairing of policies (adding one to the other) could produce an additive, negative, or neutral impact on each of the four criteria. The direction of interactions seems clear for some policy interactions on some criteria. For example, a carbon tax is likely to improve the GHG mitigation and cost-effectiveness of a light-duty vehicle policy mix, while reducing its political acceptability. As another example, I hypothesize that charger deployment is likely to improve the political acceptability and transformative signal of a policy mix. However, there is high degree of ambiguity for a large number of policy interactions – such that direction of interaction is unclear, thus necessitating further research (and more sophisticated modeling) in this area.

I also identify some research gaps. First, since qualitative frameworks (like the one I use) can indicate only the expected direction of interaction (and in some cases, not even that), empirical analysis and quantitative modeling would be required to confirm the validity of these hypotheses and estimate the magnitude of effects for particular policy mixes. For example, certain open questions remain: how would any of the three regulations (LCFS, VES or ZEV mandate) impact the cost-effectiveness of a policy mix? Or would tax carbon price improve the transformative signal when added to another policy?

Second, while climate and GHG policy focused transport literature has started to move in the direction of analyzing interactions between multiple policies using quantitative modelling (e.g., Small, 2012; Greene et al., 2014; Jenn et al., 2016; Lepitzki and Axsen, 2018; Axsen and Wolinetz, 2018; Ou et al., 2018; Jenn et al., 2019b), more work is needed in this area. In particular, while policies such as carbon taxes and vehicle emissions standards have received comparatively more focus in literature, further research may be directed towards modelling interactions of policies such as the ZEV mandate and charging deployment with other policies on effectiveness and cost-effectiveness criteria (including effect of consumers), which has rarely been examined. To conduct such analyses, models need to be equipped to realistically simulate multiple policies – including consumer and industry behavior. Also, to be able to examine development of policy interactions over time, models need to be able to simulate long-run dynamics in behavior and technology. I develop a model to address this gap, as outlined next.

6.2 Developing AUM to model supply-focused climate policy for light-duty vehicles

Technology adoption models and other transport models used for climate policy analysis have had (at least) three methodological challenges thus far, which I also outline in the Introduction chapter. First, since consumers are not perfect optimizing machines, models need to represent consumer behavior realistically, incorporating behavioral features like heterogeneity of preferences across consumers (Jaccard, 2009), inclusion of non-financial factors (e.g., technology familiarity, risk) (Lam and Mercure, 2021), as well as changes in consumer preferences over time (Axsen and Wolinetz, 2018). Second, since policy compliance, particularly for supply-focused regulations (e.g., ZEV mandate or VES), is so heavily dependent on how automakers respond to such policies, models need to represent automaker behavior endogenously. Such models should incorporate decision-making regarding compliance mechanisms like adjusting vehicle prices to change fleet mix (Goldberg, 1995; Jacobsen, 2013), or investing in R&D, or modifying vehicle characteristics (e.g., acceleration, fuel economy) (Michalek et al, 2004; Whitefoot et al, 2017). Third, since ZEV uptake is considered critical for GHG reduction, models should represent technological change features, including endogenous decreases in production costs due to increased production (or learning by doing) (Loschel, 2002) and R&D efforts (or learning by searching) (Azevedo et al, 2014). While different models have included some of these features, there has been a gap of modelling studies incorporating all three simultaneously.

To add to technology adoption modelling literature, in this work I develop the AUtomaker consumer Model (AUM), which simulates interactions between behaviorally-realistic consumers and a profit maximizing automaker. AUM represents consumer behaviour (heterogeneity and non-financial factors) and dynamic consumer preferences, and incorporates dynamic automaker learning (learning by doing and learning by searching, including feedbacks). In addition, AUM endogenously represents multi-year foresight for the automaker, including decisions about: (i) increasing ZEV model variety, (ii) intra-firm cross-price subsidies, and (iii) investing in R&D to reduce future ZEV costs. Further, this current application of the model is itself novel, which relates to examining the automaker compliance mechanisms in response to the ZEV mandate. I examine the case of Canadian auto industry which is simulated to comply with a 2030 requirement of 30% ZEV sales.

The key findings from this work are as follows. First, a ZEV mandate can potentially increase ZEV market share compared to a no-ZEV policy scenario, a result supported by other Canadian studies (e.g., Axsen and Wolinetz, 2018). I find that the Canadian auto industry is likely to cross-subsidize as the primary mechanism to comply with the ZEV mandate. Though no previous modelling effort has attempted this (and empirical on automaker pricing is typically unavailable), some market research studies support the finding that automakers are currently offering ZEVs at discounted prices relative for conventional vehicles, and are likely to do so up to 2025 or later (e.g., UBS, 2017),

Second, the ZEV mandate policy is likely to negatively impact automaker profits (with optimistic value of ~ 7% and pessimistic value of ~ 44% in 2030). Reduced sales are likely to constitute the largest proportion (64%) of the profit drop, followed by the drop in profit margin (or markup) per vehicle (19%), and higher cost of production (16% of profit loss), though the contribution of R&D spending is likely to be negligible (<1%). That said, the total automaker profits in 2030 under the ZEV mandate (on average), are likely to be higher than the profits in 2020. I also note that there is huge uncertainty over the exact magnitude of the ZEV policy impact on automaker profits, due to variations in battery costs, consumer preferences, price elasticity, and discount rate. Similar to my findings, Jenn et al's US modeling study (2018) find that a ZEV mandate could negatively impact automaker profits, as do Ou et al (2018) for their modelling study up to 2020 for China. Ou et al (2018) do not consider consumer heterogeneity, non-financial factors, or dynamic consumer preferences, while Jenn et al (2018) do not include consumers at all. Thies et al. (2016) using a systems dynamic model find that automakers' gross profits decrease slightly as electric vehicle uptake increases up to 2040, though they do not model the ZEV mandate explicitly.

This work contributes to the existing aet of technology adoption models. I believe AUM is suitable for a variety of policy-relevant applications. First, because it models policy response endogenously, AUM can be used to examine the design effects of a variety of supply-side policies more accurately, while accounting for dynamic interactions between automakers and consumers. Second, the model can be used for studying interactions between policy instruments. Policies, often implemented simultaneously, may interact in a variety of ways (Flanagan et al, 2011), and my model can be used to quantitatively examine complementarity (and other interaction) effects between different policies. Such interactions can be missed by models that represent policies as hard constraints (e.g., Jenn et al, 2018). Third, the model may also be used to analyse how automaker strategies respond to demand-side actions such as deploying infrastructure. I demonstrate one novel application of AUM in the next section.

6.3 Using AUM to simulate the impacts of ZEV mandate design

Studies of policy analysis and interactions are incomplete without a better understanding of the impacts of the various design features for a policy, a topic that is generally under studied in literature. A few studies suggest the importance of such design features. As one example, Rausch and Reilly (2012) find that a carbon tax designed such that the tax revenue is recycled could have higher economic benefits than a tax with no revenue-recycling. For vehicle emission standards, a policy design which specifies model specific fuel economy requirements is likely to lead to different vehicle features (e.g., acceleration, or vehicle footprint) in contrast to a policy design which specifies fleet-wide average standard (Whitefoot et al, 2017). However, beyond these examples, such studies of specific policy design features are scarce. In particular, there is a lack of studies examining how the various design features of the ZEV mandate (e.g., credits assigned per ZEV, allowance of banking of credits) will impact ZEV new market share. While recent studies on ZEV mandates examine the impact on automaker profitability (e.g., Jenn et, 2018; Ou et al, 2018), they do not examine how different design features affect results, instead focusing on a single idea of what a ZEV mandate might look like.

In this paper, I use AUM to illustrate the importance of the design features of a policy (in this case, a ZEV mandate) in determining overall policy impacts. I compare multiple non-compliance penalty levels to determine what penalty may be required to ensure the implementation of the ZEV mandate policy and help achieve the government target of 30% new plug-in electric vehicle market share in Canada. Moreover, I compare the effects of two ZEV mandate credit schemes: a California style credit scheme (multiple credits per BEV) and an Equal credit scheme (one credit across all ZEVs). I also assess the effect of banking credits. I utilize the AUM model to assess how policy design impacts new vehicle market share, automaker profits and consumer surplus.

From this analysis, I find that the design of the ZEV mandate could have a substantial effect on the policy's overall impact. First, I examine the effect of ZEV penalty on market share, finding that a change in ZEV penalty has a significant effect on ZEV new market share. I learn that a high penalty ZEV mandate ($ 10k/credit) may be required to achieve the government target of 30% plug-in electric market share by 2030. I also model the effect of ZEV penalty on consumer surplus and automaker profitability, to find the following. Increasing the ZEV penalty negatively affects the automaker profits. When compared to the Baseline scenario, the drop in profits in the median case was about 10% for a $2.5k ZEV penalty and 28% for a $10k ZEV penalty for the year 2030. Similarly, relative to the Baseline scenario, the drop in consumer surplus in the median case was about 12% for a $2.5k ZEV penalty and 25% for a $10k ZEV penalty for the year 2030. As noted, this is a novel application and previous literature does not quantitatively examine the design effects of the ZEV mandate. However, traces of these results can be found in certain studies. Jenn et al (2018) and Ou et al (2018) find that the ZEV mandate could negatively impact automaker profitability, lowering profits by about $2.5k per vehicle up to 2025 in U.S. and China based studies respectively.

Second, I examine the variation in total ZEV new market, automaker profitability and the composition of ZEVs under two different credit schemes (California style and Equal credit), finding that the nature of the credit scheme has a notable effect on ZEV composition. While the total ZEV market share is higher under an Equal credit scheme, the proportion of battery electric vehicles in the total ZEV mix is higher under the California style credit scheme. Change of credit scheme also has a noticeable effect on profits with lower (by 10%) automaker profits per vehicle under the California style scheme.

Third, I examine the effect of allowing automakers to bank ZEV credits over time. I find that the banking allowance has a small positive impact on automaker profits and consumer surplus. However, the effect on ZEV new market share is more pronounced. Automakers are likely to over-comply with the ZEV credits requirement in the initial years if banking of credits is allowed.

The paper makes the following contributions. First, this paper contributes to the small modelling literature examining the ZEV mandate (e.g., Greene et al, 2014; Ou et al, 2018; Axsen and Wolinetz, 2018; Jenn et al, 2018), supporting previous research that the ZEV mandate can provide a strong push to automakers to increase the supply of ZEVs and significantly increase market share compared to a no-ZEV policy scenario. Second, this paper contributes to the literature on policy design (e.g., Rausch and Reilly, 2012; Whitefoot et al, 2017), to demonstrate that that success of a policy (in this case, ZEV mandate) highly depends on the design features of the policy. Overall, though this paper looks at various impacts (e.g., ZEV market share, consumer utility, profits), it does not compare the overall cost-effectiveness of the ZEV mandate in GHG mitigation (a key research priority identified in my first paper). The final paper, outlined next, gets directly into cost-effectiveness comparisons between different policies and their policy mixes.

6.4 Using AUM to evaluate the cost-effectiveness of supply-focused regulations and policy mixes

After a deeper, policy -specific focus (i.e., ZEV mandate) in papers 2 and 3, I take a broader look at policy mixes in this fourth paper. As already noted, examination of policy mixes remains an understudied topic in transport climate policy literature (Lam and Mercure, 2021), where more commonly analyses have focussed on comparison of individual policies (e.g., Fox et al, 2017) or policy pairs (e.g., Small, 2012; Dimanchev and Knittel, 2020). In addition, to the best of my knowledge, very few transport studies make an inquiry into how cost-effectiveness of individual policies (particularly for regulations) and policy mixes varies with policy stringency (e.g., Fox et al, 2017; Small, 2012; Dimanchev and Knittel, 2020), and often with contrasting results. Small (2012) considers two stringencies per policy and finds that policy costs ($/tonne) are higher for both a higher stringency fuel tax and a higher stringency VES (compared to lower stringency versions). In contrast, Fox et al (2017) test three different stringencies of a carbon tax and ZEV mandate (though with relatively narrow ranges), finding that both can lead to lower costs ($/tonne) with higher stringencies.

In this effort, I use AUM to systematically examine multiple policy scenarios to compare and contrast the cost-effectiveness of individual policies (carbon tax, vehicle emission standard, and zero emission vehicle mandate) and their policy mixes in reaching 2030 GHG reduction goals. Further, I explore how policy costs change with changes in policy stringency. I also upgrade AUM for this study. Apart from the three endogenous automaker compliance mechanisms already included in the model – i.e. (i) increasing ZEV model variety, (ii) intra-firm cross-price subsidies, and (ii) investing in R&D to reduce future ZEV costs, I add a fourth compliance mechanism to the model:

charger deployment (more details in the SI section). That is, the automaker can endogenously contribute to the number of charging stations, which is a novel contribution to this modelling literature.

There are some key findings from this study. First, regulations (e.g., the VES and the ZEV mandate) are three times more expensive than the carbon tax in reducing GHG emissions, a result that aligns with previous literature (Fox et al, 2017; Small, 2012), but differs from Lam and Mercure (2021), who find regulations to be less expensive than taxes. However, more unique to the present study, I find the costs ($/tonne) to vary with stringency, following different patterns for each policy. Costs increase for higher carbon prices, but decrease for higher ZEV mandate stringency. A particularly unique discovery is that the VES follows an inverted U-shaped curve-like relationship between cost effectiveness and policy stringency. The VES starts of being cheaper than the ZEV mandate at lower stringencies, but at higher stringencies acts similar to a ZEV mandate, and costs decrease (or cost-effectiveness improves) with increasing stringency.

Second, I also compare the cost-effectiveness of different combinations of regulations and taxes. Adding a ZEV mandate or a VES to a tax increases policy costs ($/tonne), where such policy mixes are costlier than a tax alone by 50% (or higher). On the other hand, I find that combinations of the ZEV mandate and the VES with the tax were on average (30% or more) cheaper than individual regulatory standards. My results align with Dimanchev and Knittel (2020) and Small (2012), where combinations of tax and a VES were costlier than the tax alone, but cheaper than the VES alone. Relatedly, in some cases it seems that including both regulations (VES and ZEV mandate) may increase costs relative to including just one regulation, though that depends on the strength of the tax.

Third, among policy mixes, costs (and cost-effectiveness) also vary according to policy stringencies. Increasing the stringency of the carbon tax in a policy mix substantially reduced the costs of the mix, all else held constant. Each $50/tonne increase in tax stringency, typically leads to a 20% reduction in policy mix costs. The finding that the cost-effectiveness of policy mixes improve with increasing tax stringency is supported by Dimanchev and Knittel (2020). For the most part, increasing stringency of regulations increases policy costs ($/tonne), all else held constant. Each 20% decrease in VES emissions requirement (e.g100 g/km to 80 g/km), typically leads to 10% (or lower) increase in policy mix costs ($/tonne). For the ZEV mandate, each 10-% point increase in policy stringency (e.g., 30% to 40%) increased policy mix costs ($/tonne) by 3% or lower.

This work makes a few contributions. First, this paper provides a quantitative comparison of policy mixes on effectiveness and cost-effectiveness of GHG mitigation, thus contributing to the emerging literature on policy mixes, such as Lam and Mercure (2021). Second, the paper adds to the small literature exploring the relationship between cost-effectiveness and policy stringency (e.g., Fox et al, 2017; Small, 2012), discovering an inverted U-shaped relation between cost-effectiveness and stringency for the vehicle emission standards. The examination also yields some policy insights as discussed next.

6.5 Conclusions and Policy implications

Through my qualitative framework and quantitative modeling, I make the argument that policy analysis should more frequently investigate policy mixes and policy interactions, while considering a full range of evaluation criteria. Policy mixes can be suitable alternatives to single policies. Different policy instruments in a mix can address different criteria, such as effectiveness in GHG mitigation, cost-effectiveness, political acceptability, and transformative signal, thus potentially leading to policy suitable for reducing GHG emissions at low costs and in a political-friendly way. However, policymakers may need to consider how potential interactions between various policies affect the performance of the policy mix on each criterion. Based on my analysis, I discuss some policies which may be included in a climate policy mix.

Some common transport policies can be candidates in climate policy mixes. Starting with a carbon tax, I find that it can be effective in reducing GHG emissions when added to a policy mix, and that a sufficiently stringent tax (e.g., $350/ tonne) can meet the GHG target acting individually (chapter 5). Though implementation of individual policies at such high stringency may not be feasible due to political unacceptability, as previous research has informed us (chapter 2). Adding a tax to a mix, as well as increasing the stringency of the carbon tax in a policy mix, substantially improves the cost-effectiveness of the mix, all else held constant (chapter 5). The carbon tax leads to smaller increases in ZEV market share compared to other regulations, which suggests that it has a relatively lower transformative signalling effect. Overall, it may be recommended that policymakers implement carbon pricing in a policy mix as stringently as politically feasible (for efficiency), complemented by regulations as needed to meet GHG targets.

The ZEV mandate appears to be a good candidate to support the carbon tax, in policy mixes targeted towards GHG mitigation. It is effective in reducing emissions (chapter 5). The ZEV mandate has met with opposition from the auto industry over time, though citizens are much more likely to support it relative to a strong carbon price (chapter 2). Further, it sends a strong transformative signal by increasing ZEV market share and inducing automaker R&D in electric vehicles (chapter 3; 4). One potential weakness is that it can impose costs to automakers and consumers (chapter 3). However, careful policy design, such as choosing the appropriate scheme for allocating credits across ZEVs, can reduce profit and utility impacts (chapter 4). On this last point, policymakers may closely examine the trade-off between a higher total ZEV market share (Equal credit scheme) versus higher automaker profits and consumer utility (but lower overall ZEV market share) under the existing California scheme, in order to arrive at a suitable policy. Moreover, at stringencies required to achieve GHG mitigation, the ZEV mandate ceases to be any more expensive than the vehicle emission standards, thus strengthening the case for inclusion into climate policy mixes (chapter 5).

Analysis suggests that a vehicle emission standard (VES) is another good candidate policy. This policy too, can be effective at reducing GHG emissions, being able to meet the GHG target acting alone at sufficiently high stringencies (chapter 5). The policy generally finds support across consumers (chapter 2). The VES is more cost-effective than a ZEV mandate at lower stringencies, but at higher stringencies the two are similarly efficient and send a similar transformative signal (both incentivise widespread ZEV deployment) (chapter 5). Thus, it is difficult to pick a clear winner between the ZEV mandate and the VES for inclusion in the policy mix. In some cases, it seems that including both regulations (VES and ZEV mandate) may increase policy costs, but in other cases they might be complementary (chapter 5).

This exercise has taken a few steps towards understanding policy mixes, but is far from having learnt everything on policy mix evacuation. There is more to learn about low carbon fuel standards (LCFS), purchase incentives, charger deployment interact and influence policy mixes, which we either treat exogenously (e.g., LCFS), or do not examine explicitly (e.g., purchase incentives). For example, many open questions remain: Would a ZEV purchase subsidy produce an additive improvement in GHG mitigation or cost-effectiveness, when added to a regulation (LCFS, VES or ZEV mandate)? Would charger rollout improve GHG mitigation? How would charger deployment interact with the ZEV mandate?

6.6 Limitations and Future Research Directions

One practical priority for future research is to extend the time horizon of AUM to 2040 and beyond. The current version of AUM has a modelling horizon of up to 2030, which is an important limitation. Arguably, cost estimates of regulations (such as the ZEV mandate) could be lower when considered over the long-term, say up to 2050, as found by Lam and Mercure (2021). Relatedly, in my analysis I found that the impact of the ZEV mandate on automaker profits is affected by the length of automaker foresight. I found that the profit drop was lower (by 3%) when the automaker had a longer foresight (10 years) relative to shorter foresight (5 years). It would be interesting to see if the profit drop is even lower under a 20-year (or higher) foresight. An extension of the model to 2040 and beyond will help re-examine if a longer time horizon significantly impacts overall policy cost estimates.

A second research direction will be to examine more stringent ZEV mandates than considered in my analysis so far. Many countries are considering a 100% ZEV mandate (or a complete ban of internal combustion engines) by 2035 or 2040 (Plotz et al, 2019) – or even earlier in some cases. The feasibility and economic and GHG impacts of such an “ICE ban” remain under studied. I intend to consider more stringent ZEV mandate requirements (e.g., 50% to 100% ZEV new market share by 2035 or 2040) to examine the feasibility as well impacts of this policy goal.

Third, the model may be improved by including multiple automakers. Currently, I model just one aggregate automaker and acknowledge this is a limitation. Future model development may borrow from economics or engineering-based studies in adding multiple manufacturers and including interactions between them. For example, Goulder et al (2012) consider seven auto manufacturers and consider competition between firms, using game theory principles. Such resolution could be particularly valuable for research exploring the impacts of the ZEV mandate (and other supply-focused policies) on different automakers, say, incumbent automakers versus new entrants (e.g., Tesla).

A fourth area for extension is endogenization of other supply side actors. In particular, representation of fuel suppliers would improve the model, including incumbent fossil fuel companies, as well as the potential actions of electric utilities and hydrogen providers. Such representation would be particularly important for representation of a low-carbon fuel standard (Lepitzki and Axsen, 2018), which in some jurisdictions is likely to interact with a ZEV mandate (such as California, Quebec and British Columbia). Similar efforts might also be directed to endogenize the decisions of charging infrastructure providers.

A further research goal focuses on modelling the adoption (and effects) of transformative technological innovations such as autonomous vehicles (AVs). AVs may significantly shape the transport system in the coming years (Greenblatt and Shaheen, 2013; Fagnant and Kochelman, 2014), though there is huge uncertainty over how AVs might be adopted by consumers, and how they may impact the GHG emissions generated from the transport sector (Wadud et al, 2017). In one of the earliest notable studies on the topic, Bansal and Kochelman (2017) estimate the long-term adoption of automation in privately held light-duty vehicle fleet in the U.S. They use a technology adoption framework, with no endogenous automaker representation, and exogenously changing consumer preferences. I plan to use my model developed in the current study to investigate what market share autonomous vehicles may occupy in the private light duty vehicle fleet in the long term. The consumer choice model in AUM may need to be upgraded to add another layer in the nested discrete choice structure to include an (add AV/ not add AV) option in the vehicle purchase decisions. The willingness to pay estimates required for calculating the coefficients can be borrowed from studies such as Bansal and Kochelman (2017) and Haboucha et al (2017) or other surveys on AVs. The effect of climate policies (e.g., taxes) on AV deployment could then be examined. It will also be worth exploring if policies meant to increase ZEV sales (e.g., ZEV mandate) can impact AV uptake among consumers.

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Supplementary Information

To facilitate better understanding of the model, I include the following additional pieces of information in this supplementary information section.

S1. Framework for review- describes the three-category framework we use to review modelling literature in the main article.

S2. Model validation- describes the six-step procedure we use to validate the new model.

S3. Assumptions for uncertainty analysis- discusses the pessimistic and optimistic assumptions for the critical input parameters in the model.

S4. Results- Consumer welfare impacts – includes some of the model results where we discuss the impacts of the ZEV mandate policy on consumer welfare.

S5. Results- Effect of foresight- another set of results; discusses how model results vary on changing the length of the foresight assumed for automaker.

S6. Endogenous charging deployment

S1. Framework for review

Below we develop a three-category framework for reviewing previous modelling studies, which is then used to evaluate models in Section 3.2 in chapter 3. Table 3.1 (in chapter 3) presents the evaluation visually, with representative modelling studies listed in columns, and the three-category framework (and sub-categories) indicated in rows.

The first category of model attributes is behavioural realism (or consumer-side features), which entails that consumers be represented not as simplistic agents that make "optimal" decisions based only on financial costs, but rather as complex human beings with preferences or perceptions that might include symbolic, societal or other non-financial aspects of PEVs (Axsen and Kurani 2013; Heffner et al., 2007). Our definition of behavioural realism includes four features, namely:

- Consideration of non-financial factors: this feature recognizes that vehicle choice is affected by factors other than financial costs (Choo and Mokhtarian, 2004; McCollum et al, 2017), such as technology familiarity or awareness (Wolinetz and Axsen, 2017).
- Representation of consumer heterogeneity: this feature recognizes that different consumers in a market will have different technology preferences (Bunch et al, 2015; Higgins et al., 2017). As one example, a well-characterised model may represent multiple consumer segments to capture the heterogeneity in consumers (Brand et al, 2017)
- Empirically-informed parameters: to have behavioural realism, parameters should be informed by empirically-derived consumer data, ideally from a large, representative sample (Al-Alawi and Bradley, 2013).
- Dynamic consumer preferences: for a model with a longer time horizon (e.g., 10 years or longer), consumer preference should be dynamic, in order to be able to examine the impact of policy interventions over time (Axsen, et al. 2009).

The second broad category of technology adoption model attributes is the explicit representation of supply-side features, including transport actors (e.g., automakers and fuel suppliers), and the effect of other supply-side dynamics (e.g. lack of variety and availability in PEV makes and models). Such considerations have received little attention in transport modelling studies (Greene and Ji, 2016; Al-Alawi and Bradley,2013). Our list includes the following specific supply-side features:

- Endogenous automaker decision-making: the first feature is to endogenously represent automakers (and potentially other supply-side actors) as independent decision-making agents (Al-Alawi and Bradley, 2013).
- Representation of vehicle model class, variety and availability: a lack of variety and availability in PEV makes and models can negatively impact consumer adoption – even for consumers that have positive valuation of PEVs. Thus, a good model should represent multiple technology models, how the automaker endogenously contributes to the evolution of model variety, and how model variety affects consumer behaviour (Wolinetz and Axsen, 2017).

- Forward-looking automakers: automakers in the real-world are typically forward-looking, and their foresight is likely to influence technological innovation. Longer-term foresight (planning horizon of 10 years or more) may lead to significantly different production decisions as compared to a medium (~ 5years) or short foresight (1 to 2 years) (Klier and Linn, 2010). For example, in the long run, it may be profitable to invest in alternative fuel vehicle technologies while it may be preferred to shift prices to affect sales in the short run. Thus, a good model should be able to represent forward-looking automakers.
- Technological change (learning by doing and learning by searching): when simulating PEV uptake several years or decades into the future, endogenous learning effects can be quite important (Sterman et al., 2015). Such supply-side learning effects can be influenced by two factors: (a) learning by doing, which implies that the capital costs of new and emerging technologies decline as a result of manufacturer’s learning by doing and economies of scale (Löschel, 2002), and (b) learning by searching, includes a reduction in technology costs that may happen due to investment in R&D (Barreto and Kypreos, 2004).
- Multiple compliance mechanisms: literature suggests that automakers may respond to policies in a variety of ways- e.g. changing vehicle prices to influence sales mix (Goldberg, 1995), changing vehicle attributes (Whitefoot et al., 2017), using political strategies to negotiate policies (Wessling et al.,2014), exploiting policy loopholes to comply (Anderson and Sallee, 2011) or investing in R&D (Mazur et al., 2015) among others. Good models should thus attempt to represent some or all of the variety of compliance mechanisms that automakers may adopt.

The third category of model attributes is endogenous policy response, where a good model will be able to endogenously represent the response of consumers and automakers to a wide variety of government policies. We distinguish between two broad types of policy response:

- Supply-focused policies: These are policies which directly affect supply-side decision making, such as the ZEV mandate, fuel economy standards and low carbon fuel standards. It is difficult to simulate automaker response to (supply-focused) regulations, such as a vehicle emissions standard or ZEV mandate, so comparatively little literature has focused on such policies (Greene and Ji, 2016). However, the few studies on this subject suggest that supply-focused policies can be very powerful in driving PEV innovation and adoption (Greene et al., 2014; Lepitzki and Axsen, 2018; Lutsey et al., 2015; Sykes and Axsen, 2017), and thus should be better represented in PEV market estimation models. Moreover, automaker compliance with such policies should not be assumed or forced through hard constraints, as non-compliance with penalty is typically an option for automakers; thus, compliance should rather be endogenously determined by the model.

- Consumer-focused policies: These policies include purchase incentives, charging infrastructure or fuel taxes, that directly affect consumer decision making. For example, a fuel tax affects the fuel costs associated with a vehicle while purchase incentives can lower the purchase price of a vehicle. This second feature similarly is that the effect of consumer-side policies be endogenously included in how consumers make technology choices in the model.

S2. Model validation

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. To validate our model, we follow a six-point validation process, building upon Thies et al. (2016)'s recommendations. The six tests 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 (Jaccard et al., 2003; Gaskins and Weyant, 1993). We follow the above recommendations in our work. Table S1 depicts how our model performs on these validation tests.

Table S1: Structural validity tests for our model

Structural validity tests (from Thies et al., 2016, pp 15)	How AUM performs on these tests.
(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.	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 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 Mechalek 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 behaviourally -realistic consumer model with a detailed automaker model, rarely attempted so far.
(2) The mechanisms used within the model (e.g. learning by doing, experience spillover, purchase decisions) should be based on well-founded theories.	Learning effects build 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)
(3) The equations connecting the model variables should be dimensionally consistent.	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.

(4) The model boundary and the aggregation level should be appropriate to address the specific research questions.	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 (focuses only on light-duty vehicles) but 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.
(5) The model parameters should be based on empirical data, as far as possible	The majority of parameters in 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.
(6) Ensure that the model produces plausible, realistic output behaviour.	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 LDV 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 \$4k-\$13k CAD (Motor Monitor, 2020). Averaging over the two million vehicles sold in 2019 in Canada, this gives a value of 14-15 billion \$CAD 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 20 billion \$CAD to the Canadian economy (CVMA, 2020).

S3. Uncertainty analysis

To explore and depict the uncertainty in results, and to better understand the model, we proceed in three steps. (i) First, we identify key parameters (listed below) causing most uncertainty in model outputs. (ii) Second, we perform sensitivity analysis to explore how variation in key parameters affects key results (market share for PEVs, automaker profits, consumer surplus) in 2030, testing one assumption at a time (depicted throughout the results section). For the first four parameters listed below, (we test the effect of pessimistic and optimistic estimates drawn from literature (optimistic/pessimistic values are listed in Tables 3.2 and 3.3 in chapter 3). For the remaining parameters (5 through 9), we test the effect of varying the assumed base values by plus or minus 25%. (ii) Third, we construct a combined/composite set of optimistic/pessimistic "ranges" for key results, where the optimistic end of results emerges from the combination of the optimistic values of the key parameters. Similarly, the pessimistic values of the parameters result in the pessimistic end of the model output.

The key parameters affecting model results are:

(1) ‘Battery pack costs’ as seen by car manufacturers (including markups from battery manufacturers) are 230 CAD $/kWh in 2020, and assume values of 70 CAD$/kWh (optimistic) and 175 CAD$/kWh (pessimistic) in 2030, similar to the low (50 USD$/kWh) and high (125USD$/kWh) battery cost estimates made by Nykvist et al. (2019). In effect, PEV battery costs (which affect ‘g’ parameter in equation 8) vary by −42% to +45% relative to the base value of 120 CAD $/kWh in 2030.

(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 (Holmgren, 2007) and high (Fouquet, 2012) values suggested in literature. In effect, price elasticity varies by −50% to +66% relative to the base value of -0.6. The pessimistic and optimistic price elasticity values are constant from 2020 to 2030.

(3) ‘Discount rate’ used by the automaker assumes values of 8% (optimistic) and 15% (pessimistic), corresponding to the low and high values suggested in Jagannathan et al. (2016). In effect, discount rates vary by −20% to +50% relative to the base value of 10%. The pessimistic and optimistic discount rate values are constant from 2020 to 2030.

(4) ‘Fuel prices’ (petroleum) are taken to be 70 $CAD/bbl in 2020, and assume values of 92 $CAD/bbl (pessimistic) and 177 $CAD/bbl (optimistic) in 2030, corresponding to 2 US $/gallon (60 US $/bbl) and 4.23 US $/gallon (~ 128US $/bbl) oil price scenarios (NEB, 2019; U.S. EIA, 2020), or −27% to +40% of the base price assumption of 125 $ CAD/bbl. in 2030.

(5) ‘Foresight’ parameter assumes two values: 5 year (pessimistic, representing a medium-term foresight) and 10 year (optimistic, indicating a long-term foresight), in line with previous studies (Klier and Linn, 2012).

(6) The ‘Consumer preferences’ parameter, representing the endogenous change of ASC over time, varies across consumer segments (Table 2). As an example, the consumer preference for BEVs among the “Resistors” consumer segment is -40k CAD$ in 2020, and assume a base value of -28k CAD$, with -35k CAD$ as pessimistic and -21k CAD$ as optimistic values in 2030.

(7) The exogenous global increase in ‘Model variety’ for PEVs is assumed to grow from 10% (relative to model availability for conventional vehicles) in 2020, to assume values of 40% (pessimistic) and 90% (optimistic) in 2030, with a median value of 70%, similar to Wolinetz and Axsen (2017).

(8) The ‘Recharging access’ parameter, indicating the locational availability of public charging infrastructure, relative to existing gasoline infrastructure, is 10% in 2020, and assumes values of 50% (pessimistic), 70% (base) and 90% (optimistic) in 2030.

(9) In general, the rate of learning indicates the percentage drop in vehicle costs for every doubling of cumulative capacity of vehicles or knowledge stock. In our model, however, the ‘Rate of learning’ . parameter determines the rate at which technology improves in Canada, partly (in addition to global efforts) affecting how quickly domestic vehicle manufacturing costs drop over time, in response to increased domestic production (learning by doing) or domestic investment in R&D (learning by searching) (see equation 8 for reference). Since part of the decline in vehicle costs is assumed to be exogenous (due to global factors), this rate of learning can be understood to be the ‘domestic’ learning rate. The Rate of Learning parameter assumes values of 6% (pessimistic) and 10% (optimistic), +/- 25% relative to the base value of 8% (Weiss et al., 2012), These values are constant from 2020 to 2030.

S4. Consumer welfare impacts

Fig. S1 depicts the effect of the ZEV mandate policy on the range of the BEVs chosen by consumers. As noted in the methods section 3.1 of the main manuscript, consumers in our model can choose from five BEV range types (BEV-100km, BEV-180km, BEV-240km, BEV-320km and BEV-380km). Fig. S1 depicts the proportion of BEV-100 vehicle type among the five BEV range vehicles. The proportion of BEV-100 vehicles decreases in the Baseline, indicating that consumers' uptake of smaller range BEVs decreases (and uptake of large -range BEVs increases), caused largely due to the exogenous global improvement in technology and reduction of costs of longer range BEVs. The national level ZEV mandate in Canada contributes towards marginally accentuating this effect.

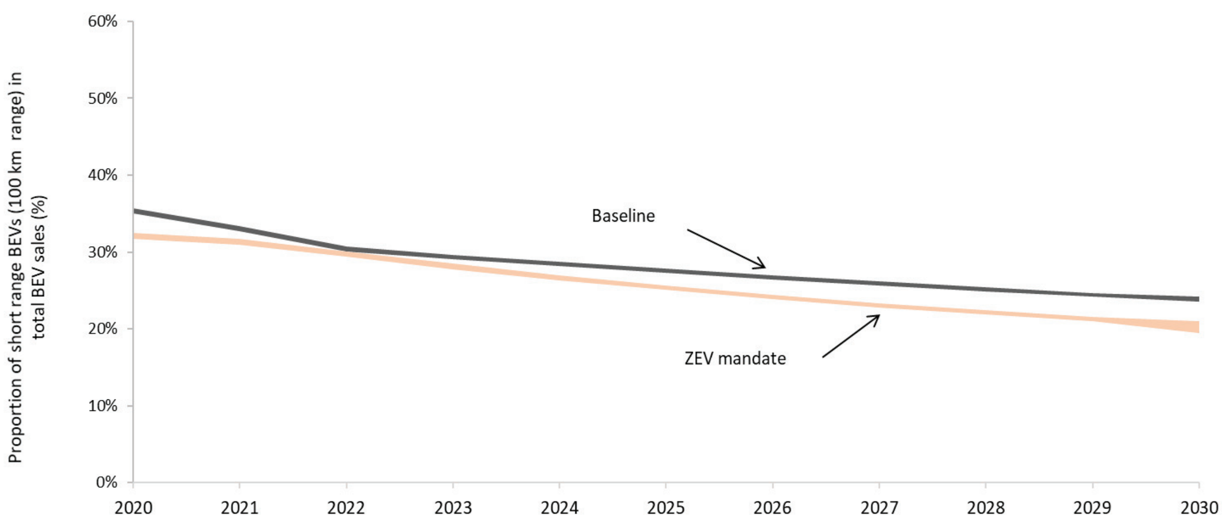

Fig. S1 Difference in the composition of the total BEV sales (by range type) under the ZEV mandate and the Baseline scenario

Fig. S2 depicts the change in consumer surplus under the ZEV mandate relative to Baseline. In 2020, the ZEV mandate reduces consumer surplus (estimated as shown in equation 2b in the main article) by between 4 to 13 billion CAD$ (or 12% to 38% respectively) compared to the Baseline. There is large uncertainty in these the estimates, depending on critical parameters such as battery costs, model variety, consumer preferences, price elasticity, recharging access, and fuel price, as depicted in Fig. S3.

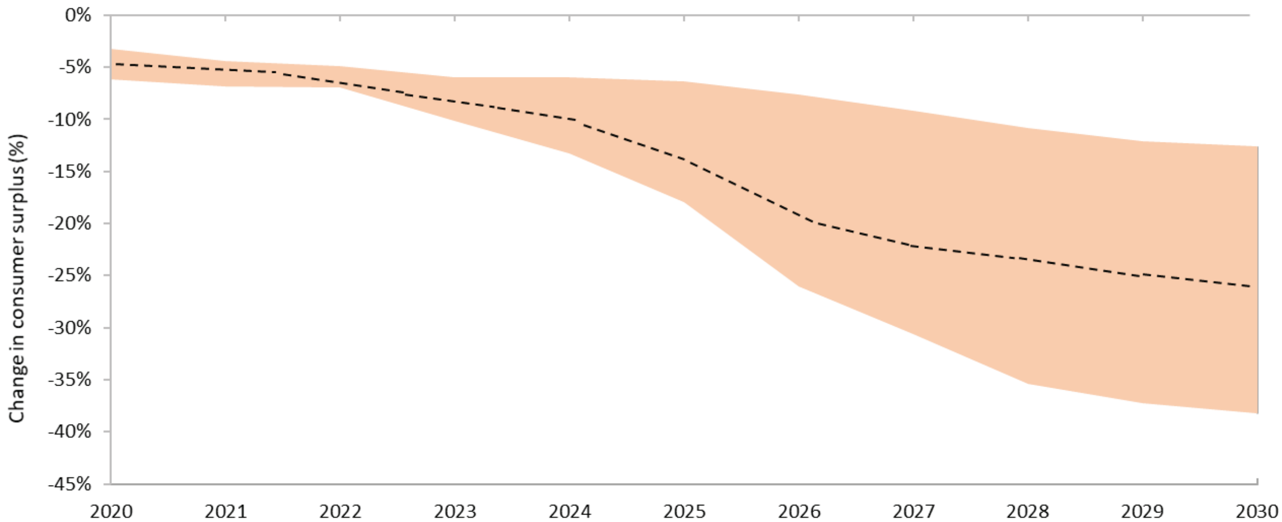

Fig. S2 Change in consumer surplus under ZEV mandate policy scenarios (relative to Baseline), with shading representing the uncertainty due to parameters, with corresponding sensitivity results in Fig. S3.

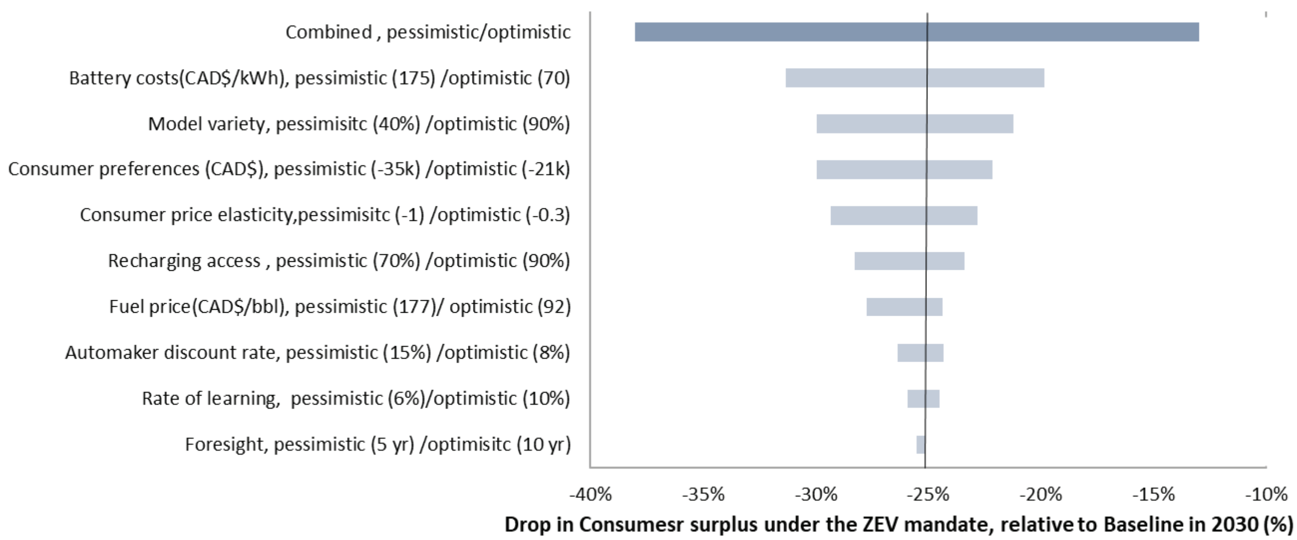

Fig. S3 Sensitivity analysis of the change in consumer surplus under the ZEV mandate (relative to Baseline) in 2030

S5. Effect of foresight

To examine the effect of foresight, we run the model under two cases: one with a 5-year foresight and a second with a 10-year foresight. We estimate the total automaker profits (cumulated over 2020-2030) for the two cases. We observe that the length of foresight does have an effect (albeit small, ~ 1%) on profits, such that longer foresight (10-year) leads to more cumulative profits (177.95 billion $CAD) than for a shorter foresight (176.19 billion $CAD).

When automakers are assumed to have a longer foresight, they are willing to incur higher short-term costs to gain larger long-term gains. This effect can be seen in Fig. S4i-ii, which depicts the change in annual automaker profits under the 5-year vs 10-year foresight cases. By charging relatively lower average markups (see Fig. S5) automaker profits are relatively lower in the initial years under the 10-year foresight case. Lower markups facilitate higher PEV market share sooner, which in turn contributes towards increasing consumer preferences towards PEVs sooner. Increased consumer preferences allow the automaker to charge higher markups and thus earn higher profits in the later years and overall. The effect of foresight is expected to be more pronounced for an ever longer foresight (20 years or so). One might argue that if the ZEV mandate gives a clear long-term signal to automakers, inducing them to plan for the longer term (up to 2040 or so), it may contribute to marginally higher profits. In the current analysis, we examine the effect of changing the foresight of the industry as a whole. However, we acknowledge that different automakers may have differing foresight horizons. We hope to consider it in a future study.

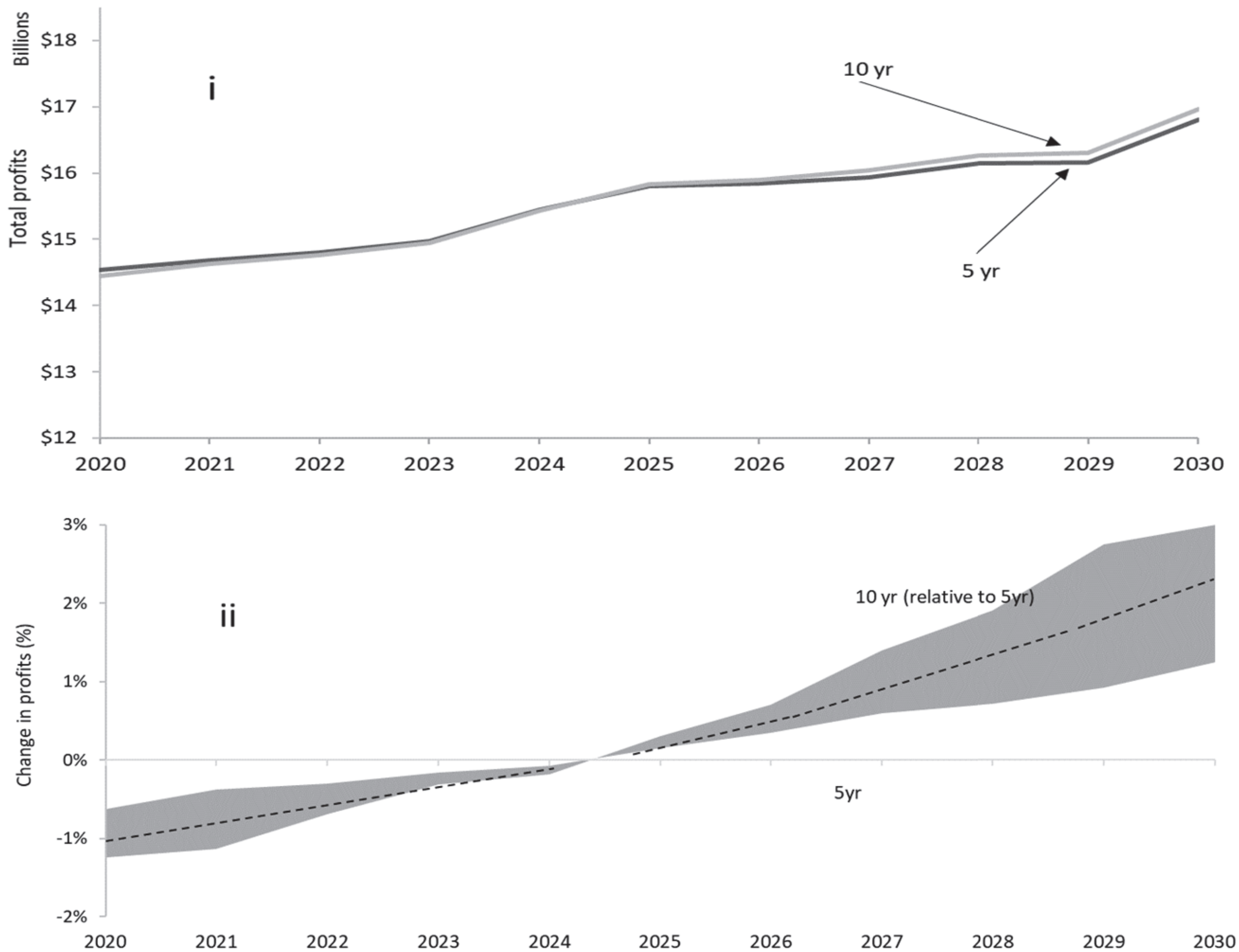

Fig. S4 Annual profits (Fig. S4i) and % change in profits (Fig. S4ii) for a 10-year foresight (relative to a 5 -year foresight)

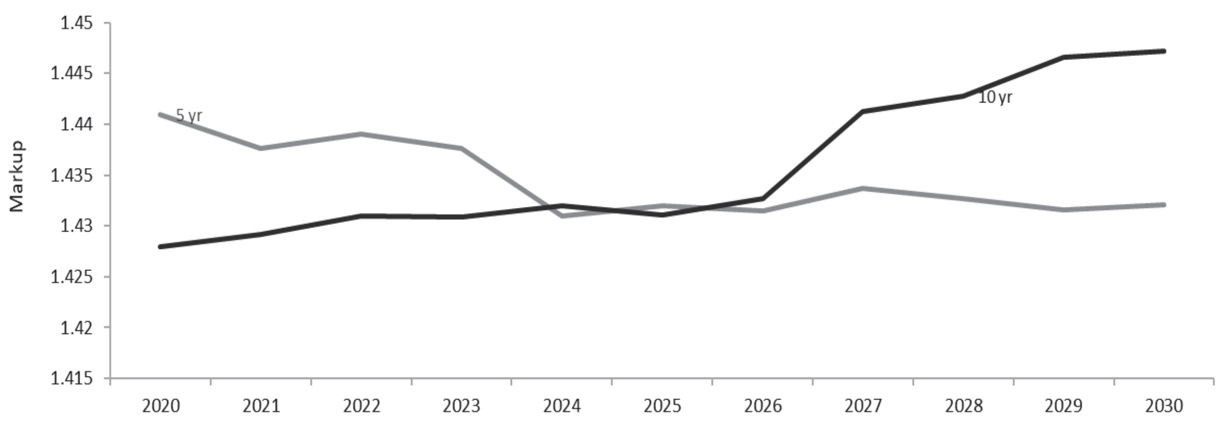

Fig S5 Effect of foresight on Average markup across all vehicles. It can be seen that with a 5-year foresight the average markup is higher initially but falls in the later years. With a higher foresight (10-year), automaker is willing to sell vehicles with a lower markup which allows a higher markup in the later years.

S6. Endogenous charging deployment

During the preparation for chapter 5, I upgraded the model. Apart from the three endogenous automaker compliance mechanisms already included in the model – i.e. (i) increasing ZEV model variety, (ii) intra-firm cross-price subsidies, and (ii) investing in R&D to reduce future ZEV costs, I add a fourth compliance mechanism to the model: charger deployment. The resulting automaker equation is as follows

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

$$Profits = \sum_{t=1}^{T} \frac{1}{(1+i)^t} \sum_{k=1}^{K} [Q_{tk}(P_{tk}, n_{ctk}, CA_{ctk}). P_{tk} - C_{Ptk} - C_{Rtk} - C_{Itk}] \qquad \text{(S1)}$$

Where, $Q_{tk}(P_{tk}, n_{ctk}, CA_{ctk})$ is the quantity of each vehicle type *k* produced in t^{th} time period and quantity is a function of price P_{tk}, and number of models n_{ctk} of the vehicle type *k*. n_{ctk} is endogenously added by the Canadian automaker, in addition to the exogenous increase in the number of models globally. Similarly, CA_{ctk} is the Canadian automaker's endogenous contribution to charging access (in %), in addition to the exogenous increase in charging access. 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 rest of the equations in the model remain the same as described in chapter 3.