Does a region need its own zero emission vehicle mandate, or can it free-ride off another? Modelling British Columbia and California

by

Maxwell Sykes

HBA, Ivey Business School at Western University, 2007

Project Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Resource Management (Planning)

in the
School of Resource and Environmental Management
Faculty of Environment
Report No. 623

SIMON FRASER UNIVERSITY

Spring 2016

Approval

Name:	**Maxwell Sykes**
Degree:	**Master of Resource Management (Planning)**
Title:	***Does a region need its own zero emission vehicle mandate, or can it free-ride off another? Modelling British Columbia and California***
Report No.	**623**
Examining Committee:	**Chair:** Mikela Hein Master of Resource Management Candidate

Jonn Axsen
Senior Supervisor
Assistant Professor

Mark Jaccard
Supervisor
Professor

Date Defended/Approved: January 27, 2016

Abstract

Policymakers are investigating how to transition to zero emission vehicles (ZEVs) to achieve long-term GHG targets. ZEV adoption is limited by regional and global barriers, where reductions in global barriers spill over between regions. I use an energy-economy model to investigate whether a smaller North American region (British Columbia) needs its own strong ZEV policy or can instead free-ride off spillovers from policy in other jurisdictions (California and other ZEV States) to achieve their GHG target. I find that 50% of new vehicles sold in 2040 and over 90% in 2050 need to be ZEVs, and that these adoption levels likely cannot be achieved through free-riding. Rather, regions likely need their own strong ZEV policy alongside other vehicle and fuel policies, even under optimistic assumptions about technological progress. Moreover, regions with strong ZEV policy may lower GHG abatement costs 11-48% by convincing other jurisdictions to follow with similar policy.

Keywords: zero emission vehicle; electric vehicle; LCFS; CAFE standard; climate policy; low-carbon technology

Dedication

I dedicate this work to my dad, Clive, who passed just before I began my Master's, but whose lessons stuck with me throughout it.

Acknowledgements

Professionally, I owe a great deal of my growth and development over the past few years to the guidance, patience, support, and critique provided by my supervisor Dr. Jonn Axsen. Thanks Jonn. Thank you also to Dr. Mark Jaccard for bringing his knowledge and perspective to my project at critical junctures, and particularly for offering guidance intended to help make my work acceptable to a wider audience so as to increase the impact of my efforts. Thank you also to my colleagues in in the Energy and Materials Research Group and in SFU’s School of Resource and Environmental Management for their insights and encouragements.

Personally, I would not be who or where I am without my family. Thank you to my mom, Pamela, and step-dad, John, who both always strive to give me every opportunity they can, supported me throughout my masters, and I know will always be there for me in the future. And thank you to my soon-to-be bride, Devin, for being the greatest partner in this life a guy could ask for.

Finally, I would like to acknowledge the financial funding granted to me by the Social Sciences and Humanities Research Council of Canada, the Energy and Materials Research Group, Simon Fraser University, and the School of Resource and Environmental Management.

Table of Contents

List of Tables

List of Figures

List of Acronyms

AEO2014	*Annual Energy Outlook 2014*
BEV	Battery electric vehicle
CAD	Canadian dollars
CAFE	Corporate average fuel economy
CARB	California Air Resources Board
GHG	Greenhouse gas
GJ	Gigajoule
EIA	United States Energy Information Administration
HFCV	Hydrogen fuel cell vehicle
LCFS	Low carbon fuel standard
PHEV	Plug-in hybrid electric vehicle
tCO_2e	Tonnes carbon dioxide equivalent
U.S.	United States
VKT	Vehicle kilometres travelled
WTW	Well-to-wheel
ZEV	Zero emission vehicle

Chapter 1.

Introduction

1.1. Zero emission vehicles and long-term greenhouse gas reduction targets

Zero emission vehicles (ZEVs)—which have zero tailpipe emissions—are expected to play a critical role in achieving long-term greenhouse gas (GHG) reduction targets, i.e. cutting emissions by 80% by 2050 (Kyle and Kim, 2011; Williams et al., 2012). ZEVs commonly include three vehicle technologies. Battery electric vehicles (BEVs) are powered solely by electricity. Plug-in hybrid electric vehicles (PHEVs) are powered by electricity for a limited range, then by petroleum or biofuel. Hydrogen fuel cell vehicles (HFCVs) are powered by hydrogen. In the short-term, studies estimate that ZEVs could reduce GHG emissions by 15% to 79% relative to conventional petroleum-fuelled vehicles (Axsen et al., 2015; Duvall et al., 2007; Samaras and Meisterling, 2008; Stephan and Sullivan, 2008). These estimates depend on social and technical assumptions, such as individual driving patterns (for PHEVs) and a region's source of electricity (for BEVs and PHEVs). In the long-term, ZEVs offer the potential to achieve 2050 GHG reduction targets if regions transition to low carbon electricity systems and suppliers reduce the GHG intensity of hydrogen production (NRC, 2013).

Adoption barriers stem from technology characteristics and consumer preferences that can make ZEVs more expensive and less attractive than conventional vehicles. For example, limited driving range makes BEVs less attractive to some drivers accustomed to the longer range of conventional vehicles (Franke et al., 2012; Sierzchula et al., 2014). Similarly, a perceived or real lack of public electric vehicle charging and hydrogen fuel stations can also make these vehicles less attractive (Sierzchula et al., 2014). The higher capital cost (vehicle price) of ZEVs relative to conventional petroleum-fuelled vehicles also limits adoption (Egbue and Long, 2012). Furthermore, drivers have varying needs and preferences for their vehicles, so interest in ZEVs will likely remain low if available vehicle models lack diversity (e.g. size, power, cost) (Struben and Sterman, 2008). This list of barriers is not exhaustive, but indicates the kind of financial and non-financial issues that must be addressed to significantly increase ZEV adoption.

Strong, sustained, ZEV-specific policy is likely needed to lower ZEV adoption barriers in time to achieve long-term GHG targets (Greene et al., 2014a, 2014b). Pricing GHG emissions, such as through an economy-wide carbon tax, is commonly considered by economists to be the most cost-effective way to reduce GHG emissions (Field and Olewiler, 2011). However, some energy researchers argue that such pricing policies alone may not provide the market signals necessary to cost-effectively overcome specific adoption barriers (Azar and Sandén, 2011; Carrillo-Hermosilla, 2006; Stern, 2007). Furthermore, research from British Columbia indicates that citizens may be less opposed to climate regulations than taxes (Rhodes et al., 2014). Rather, policies targeting specific adoption barriers may be necessary in combination with policies that specifically target GHG emissions (e.g. carbon tax), which may still be the most important single element to a cost-effective GHG reduction strategy (Jaffe et al., 2005). These ZEV-specific policies likely need to induce technological advancements in vehicles, increase refuelling infrastructure, lower vehicle costs, align market offerings with consumer preferences, and increase consumer confidence that ZEVs can satisfy driving needs (Bakker and Farla, 2014; Gordon et al., 2012). The influence that adoption barriers—and the policies meant to overcome them—have on a region's level of ZEV adoption depends on developments occurring both within and outside the region (Lutsey et al., 2015). For this study, I use the terms regional barriers and global barriers. Regional barriers depend primarily on developments within a region, whereas global barriers depend primarily on developments that transcend regional boundaries. For example, two commonly cited adoption barriers limiting BEV adoption are limited driving range and a perceived lack of sufficient public charging stations (e.g. Sierzchula et al., 2014). A BEV's driving range depends on the decisions of automakers that design, build, and market vehicles, so I classify limited driving range as a global barrier. I classify public charging infrastructure as a regional barrier because the placement and abundance of charging stations depends primarily, though not entirely, on decisions made by regional governments and businesses (Lutsey et al., 2015). To significantly increase ZEV adoption, regions may need policies that target both regional and global adoption barriers.

Because developments outside a region can affect the way consumers experience adoption barriers inside a region, regional policymakers have an incentive to free-ride off policy in other jurisdictions. A free-rider problem, occurs whenever a person, government, or other actor cannot be excluded from spillover benefits that result from the efforts of others (Ostrom, 1992). This problem can occur for global ZEV adoption barriers. For example, when one region or nation provides R&D funding to advanced automotive battery manufacturers, any improvements in battery technology (e.g. reduced costs or increased power or energy density) are not just limited to that one region. Rather, the battery improvements spill over into other regions. These other regions have an incentive to maximize the net benefit gained from the battery improvements by minimizing their contribution to the R&D funding. Given the long timelines, high upfront costs, and significant uncertainty involved in transitioning to ZEVs (e.g. Fischer and Newell, 2008; NRC, 2013), governments that believe they can achieve their long-term GHG target by free-riding off ZEV-supporting policy in other jurisdictions have an incentive to do so. (This incentive to free-ride may exist in any situation where a region believes free-riding off policy in another region may make achieving policy objectives more cost-effective.) Presently, however, it is unclear whether employing such a strategy of free-ridership would allow a region to achieve its long-term GHG target—in part because the relative importance of global versus regional barriers is unknown.

This study investigates the importance of regional ZEV policy in achieving long-term GHG targets and the opportunity for smaller North American regions to free-ride off stronger policy in other jurisdictions. I analyze the case study of British Columbia in the context of California's ZEV mandate—a policy that requires automakers to sell a minimum market share of ZEVs in the state—using a simulation model of the North American passenger vehicle sector. The model represents global and regional adoption barriers, endogenous technological change, and dynamics in consumer preferences. I use Monte Carlo simulations to account for uncertainty and generate probabilistic estimates of vehicle adoption, GHG reductions, and GHG abatement costs.

1.2. Categorizing pro-ZEV policies

Policies that specifically target ZEVs or other alternative fuel vehicles can be categorized as demand-focused or supply-focused, both of which may be important to overcome the regional and global barriers limiting ZEV adoption (Axsen et al., 2015). Demand-focused policies aim to stimulate consumers to buy ZEVs by lowering adoption barriers directly, for example by offering a purchase incentive to reduce the price. Conversely, supply-focused policies stimulate automakers to increase the availability of ZEVs and help develop the ZEV market. Supply-focused policies, thus, influence automakers to take action to lower adoption barriers, for example by reducing the purchase price, offering a wider variety of ZEV makes and models for sale, or increasing marketing efforts to sell ZEVs.

Common demand-focused ZEV policies include purchase incentives, information campaigns, and investments in refuelling infrastructure (Lutsey et al., 2015). Monetary incentives lower the incremental cost to purchase or own a ZEV relative to conventional vehicles. Examples include subsidies, tax exemptions, and tax credits on both vehicles and electric vehicle home charging stations. Non-monetary incentives provide consumers a benefit to ZEV ownership unavailable to other drivers, such as access to bus lanes or exemption from systems that limit driving days. Information campaigns can help familiarize consumers with ZEV technology, inform people about local vehicle availability, and explain some of the private benefits of ownership. Finally, perhaps the most common demand-focused policies concentrate on building hydrogen fueling stations and electric vehicle charging infrastructure. Governments may build such infrastructure themselves, require new developments to install electric vehicle chargers, or incentivize the installation of chargers. Each of these demand-focused policies requires some sort of voluntary participation and may need to be combined with regulations or market-based instruments to create sufficient pressures to guide industries on a path towards lowering GHG emissions to a sustainable level (de Bruijn and Norberg-Bohm, 2001).

With the exception of research and development support, three supply-focused transportation policies in North America may stimulate suppliers to increase ZEV production and take action to lower adoption barriers.[1] Two of these policies do not explicitly target ZEVs, but have mechanisms that may incentivize ZEV production and marketing. The corporate average fuel economy (CAFE) standards are harmonized GHG emission and fuel economy standards have been adopted by both the United States (U.S.) and Canada (P.C., 2014). CAFE requires automakers to both decrease the average GHG intensity and increase the average fuel economy of their vehicle fleets (CFR, 2012). During the first few years of implementation, CAFE encourages ZEV production by counting ZEVs as multiple vehicles in fleet averaging calculations and assuming BEVs and HFCVs emit zero emissions.[2] The U.S. Environmental Protection Agency projects that electric vehicles need to make up about 2% of new vehicle market share in 2025 for fleet-wide CAFE compliance (U.S. EPA, 2012a).

In addition to CAFE, California and British Columbia have enacted low carbon fuel standards (LCFS) that require fuel suppliers to reduce the carbon intensity of their fuels (CCR, 2010; SBC, 2008). In California, suppliers can comply with LCFS by purchasing credits from producers of electricity and hydrogen, both of which have been deemed to meet the carbon intensity requirements through 2020 (CARB, 2011). British Columbia's LCFS classifies electricity as more than 80% less GHG-intensive than any other fuel (BC MEM, 2013). As such, both regulations encourage electric utilities and hydrogen fuel providers to support ZEV deployment (e.g. through investment in fuel infrastructure), although any effect will likely be relatively small compared to other ZEV incentives, e.g. in the range of one to several hundred dollars per year per BEV (Yang, 2013, p. 61).

The third supply-focused ZEV policy in North America is California's ZEV mandate. The ZEV mandate requires automakers to sell increasing numbers of ZEVs in the state each year or pay fines, effectively forcing automakers to invest in developing the state's

---

[1] ZEV policies also exist outside North America, but are not discussed here. For example, Norway uses a portfolio of demand-focused policies, including monetary incentives that can make BEVs as affordable as conventional vehicles by exempting BEVs from the country's exceptionally high purchase taxes (Hannisdahl et al., 2013; The Nordic Page, 2015). Additionally, like CAFE and LCFS, the European Union's supply-focused carbon dioxide emissions standards have mechanisms that may stimulate ZEV supply and marketing (EC, 2014).

[2] BEVs and HFCVs count as two vehicles beginning in 2017 and phase down to 1.7 vehicles by 2021. PHEVs count as 1.6 vehicles in 2017 and phase down to 1.3 by 2021. All BEVs and HFCVs count as zero emissions until 2021. From 2022 onward a limited number of BEVs and HFCVs count as zero emissions, beyond which automakers must account for upstream emissions from electricity generation and hydrogen production (U.S. EPA, 2012b).

ZEV market (Vergis and Mehta, 2012). I use the ZEV mandate as the central policy in my simulations. The next section provides further background on this policy.

1.3. The California ZEV mandate

California policymakers have determined that ZEV supporting policy will play a critical role in any strategy that achieves the state's 2050 GHG reduction target (80% below 1990 levels). Specifically, the California Air Resources Board (CARB) (2009) estimates that all new passenger vehicles sold in 2040 must be BEVs or HFCVs, even with more fuel efficient vehicles, less GHG intensive fuels, significantly higher biofuel availability, and lower vehicle travel demand. PHEVs play a transition role, but no new PHEVs are sold starting in 2040.

To achieve this level of ZEV adoption, California has implemented both demand- and supply-focused ZEV policies as part of a multi-pronged approach to reducing passenger vehicle emissions targeting vehicles, fuels, and mobility (Sperling and Eggert, 2014). The state is aiming to stimulate vehicle supply and marketing with its ZEV mandate, and stimulate consumer demand through the policy instruments included in its *2013 ZEV Action Plan* (California Governor's Office, 2013). The ZEV Action Plan includes vehicle rebates, investments in refuelling infrastructure, high occupancy vehicle lane access, and consumer awareness programs.

California originally designed the ZEV mandate to reduce smog-forming pollutants then expanded it to include GHGs in 2004 (Collantes and Sperling, 2008). The ZEV mandate is a compulsory regulation that puts the onus on automakers to develop the ZEV market by requiring them to earn a minimum number of ZEV credits each year (CCR, 2015). Individual vehicles are eligible for different number of ZEV credits depending on their zero emission range. For example, as of 2015, a HFCV with a 300 mile (483 km) range is worth 4.0 credits, a BEV with a 100 mile (161 km) range is worth 1.5 credits, and a PHEV with a 50 mile (80 km) electric range is worth 1.0 credit (Lutsey et al., 2015). Automakers who do not earn the minimum required ZEV credits face fines of $5,000 per vehicle (Lutsey et al., 2015). Annual ZEV credit requirements are based on the total number of vehicles an automaker makes available for sale in the state. For example, if an automaker produces and delivers for sale 100,000 vehicles in California and the ZEV credit requirement is 5%, the automaker requires 5000 credits to comply. ZEV credit requirements increase each year. Automakers can acquire credits either by producing and delivering ZEVs for sale in California, or purchasing excess ZEV credits from other automakers whose production and delivery of ZEVs enabled them to exceed the minimum ZEV credits required. The mandate is also designed to favour increasing numbers of BEVs and HFCVs over time by decreasing the proportion of ZEV credits that automakers can earn with PHEVs. With support from the ZEV mandate, BEVs and PHEVs are expected to constitute approximately 15% of California's new vehicle sales in 2025 (Lutsey et al., 2015).

In 2013, nine other states adopted California's ZEV mandate under Section 177 of the *Clean Air Act* (U.S. EPA, 2015), including Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont. With California, these "ZEV States" represent approximately 25% of the U.S. passenger vehicle market (Center for Climate and Energy Solutions, 2013). Currently, automakers can earn credits in any state covered by the ZEV mandate and use them to comply with credit requirements in any other ZEV State (e.g. ZEVs sold in California count towards requirements in Massachusetts) (Voelcker, 2015). Starting in 2018, however, provisions in the mandate will compel automakers to meet ZEV credit requirements in each ZEV State individually (e.g. ZEVs sold in California will only count towards requirements in California).

In 2014, despite having just 12% of the U.S. population, more than half of U.S. electric vehicle sales occurred in California (Cobb, 2015).[3] New vehicle market share in California was 3.3% compared to 0.73% in the U.S. as a whole (IHS Automotive, 2015). California ranked higher than any other U.S. state and only Norway and the Netherlands achieved higher market shares when the sub-national California is compared to national regions (Lutsey et al., 2015). An analysis of four automaker strategies in response to the ZEV mandate found that vehicle suppliers have shifted from more defensive political strategies to more proactive strategies involving technological innovation and efforts to shape, and even support, the mandate (Wesseling et al., 2015). Automakers also tend to market and sell a wider variety of models in California than in other regions; for example, four of the five cities with the most BEV and PHEV models available are located in

---

[3] HFCVs are not yet being sold in large numbers anywhere.

California (Lutsey, 2015), which could mean that consumers in those regions are more likely to find a ZEV that they are interested in purchasing. The wider variety of vehicle models may be one reason California electric vehicle sales are higher than projected ZEV mandate requirements through 2016 (Lutsey et al., 2015).

Potential critiques of the ZEV mandate focus on economic efficiency and political acceptability. The main critique has been that forcing automakers to produce certain vehicle technologies is less cost-effective than directly taxing or regulating GHG emissions (Dixon et al., 2002; Ferrara, 2007). Cost-effectiveness is a common critique of policies that focus on specific technologies (e.g. Jaffe et al., 2005; Nordhaus, 2011), but has been challenged by others that argue technology-specific policies are needed to stimulate long-term innovation activities and to overcome adoption barriers and the path-dependence of incumbent technologies (Azar and Sandén, 2011). A lack of cost-effectiveness was also cited as a major criticism by auto and oil companies that lobbied against the ZEV mandate when it was originally enacted (Brown, 2001) and filed lawsuits when an updated version of the mandate took effect in 2002 (O'Dell, 2002). Although automaker resistance to the ZEV mandate has decreased over time (Wesseling et al., 2015), industry resistance may still affect the political acceptability of a policy that forces sales of alternative fuel vehicles. For example, in September 2015 California's Governor cited oil industry lobbying as a key reason for the defeat of a bill that would have required a 50% reduction in petroleum use in vehicles (Senate Bill 350) (Siders and White, 2015). Still, in the context of needing strong policy to reduce GHG emissions, research out of British Columbia indicates that citizens may be less opposed to climate regulation than taxes (e.g. California's ZEV mandate over Norway's exceptionally high taxes on conventional vehicles or a high carbon tax) (Rhodes et al., 2014). Despite the potential for industry opposition and critiques about the cost-effectiveness of the ZEV mandate, California strengthened the mandate in 2012 and extended it to 2025, and nine other U.S. states adopted the mandate since then (Sperling and Eggert, 2014).

1.4. Other studies that have modelled the ZEV mandate

Research focused on achieving California's long-term GHG targets has consistently found that the ZEV mandate plays a critical role. Three studies have used a combination of GHG inventory models and optimization models that seek to identify abatement pathways that minimize abatement costs. Wei et al. (2013) found that achieving the state's overall 2050 GHG target requires at least 94% of passenger vehicles to be BEVs and PHEVs (the authors excluded HFCVs due to multiple challenges posed by hydrogen distribution, storage, fuel cell technology, and cost). Yang et al. (2015) found that, barring advances in biofuels and carbon capture and storage technology, approximately 90% of passenger vehicles must be BEVs and HFCVs by 2050, with the remaining 10% being PHEVs. Greenblatt (2015) modeled three policy scenarios across multiple sectors to explore what level of GHG reductions can be achieved through previously proposed California climate policies. Even the most stringent set of policies achieved only a median of 59% GHG reductions (target = 80%). In this scenario, 60% of the passenger vehicle fleet is ZEVs by 2050, indicating that a higher share of ZEVs may be needed. Of these studies, only Yang et al. (2015) simulated consumer behaviour and adoption barriers, and none represented dynamics in technology or consumer preferences, nor considered spillovers to other regions without a ZEV mandate.

An analysis of automaker strategies to comply with the ZEV mandate suggests that the mandate may effectively stimulate automaker participation in ZEV marketing efforts. Walther et al. (2010) used a simulation model to examine automaker strategies to comply simultaneously with two of California's passenger vehicle policies between 2009 and 2021: the ZEV mandate and low emission vehicle regulations. In the study, the ZEV mandate requires automakers to earn ZEV credits equal to 16% of their vehicle sales starting in 2018. Automakers are modeled as wanting to sell vehicles by selecting what types and how many vehicles to supply in four vehicle segments (defined by size and weight) based on policy requirements, production costs, and consumer demand. Conventional vehicle costs increase with fuel efficiency improvements while ZEV costs are based on the type of ZEV and battery range, where vehicles worth more ZEV credits cost more. Consumers are modeled to purchase vehicles based on price, driving range, and refuelling station availability. To avoid ZEV mandate fines, Walther et al. found that automakers must focus on lowering adoption barriers across a wide variety of potential purchasers by marketing a variety of ZEVs, especially BEVs worth more credits, in all vehicle segments as early as possible, even while demand is still low.

Two studies by Greene et al. (2014a, 2014b) investigated ZEV transition policy scenarios using LAVE-Trans, a consumer choice model of the U.S. passenger vehicle sector that was also used in the U.S. National Research Council's study *Transitions to Alternative Vehicles and Fuels* (NRC, 2013). Consumers in LAVE-Trans purchase vehicles based on price and a set of adoption barriers representing diversity, majority, public fuel and recharge station availability, range, refuelling time (for HFCVs), and range anxiety (for BEVs). Greene et al. split the model into two regions—the ZEV States and the rest of the U.S.—in part to account for the effects of regional spillovers that affect vehicle prices and adoption barriers. The principal scenario in both studies features a set of "plausible" ZEV policies involving a combination of ZEV mandates, vehicle subsidies, and fuel infrastructure installations at a combined stringency necessary to reduce GHGs 80% by 2050 (2014b, p. 36).[4] Even with a California LCFS and U.S. CAFE standard until 2050, Greene et al. (2014a, 2014b) found that ZEVs play a critical role in achieving the 2050 GHG target, that strong policies targeting vehicles and fuels are likely needed to overcome adoption barriers, and that the transition yields net economic benefits. The authors find that by 2050, 75% of new vehicle sales must be ZEVs; if the ZEV transition policies are removed, the "very significant" CAFE and LCFS policies (2014b, p. 44) achieve only 55% GHG emissions reductions (target = 80%).

Greene et al. (2014a) briefly discuss the results of a Global Market scenario that, like my present study, was designed to see how much regional spillovers from international ZEV sales would assist the transition to ZEVs in the ZEV States. In this scenario, ZEV States end their ZEV mandate in 2025, the rest of the U.S. does not transition to ZEVs, and an exogenous international region increases ZEV new vehicle market share to 20% by 2030 and 50% by 2050. The authors found that international sales trigger scale economies and learning by doing that lower ZEV prices in the ZEV States, but do not create the diversity of choice or regional refuelling infrastructure required to lower non-financial adoption barriers. ZEV new vehicle market share in the ZEV States reaches 45% by 2035 and 65% by 2050, but this is not enough for California to reach its 2050 GHG target.

---

[4] Specific stringencies are not provided.

1.5. Research approach and objectives

This study investigates whether smaller North American regions can achieve long-term GHG targets by free-riding off stronger ZEV policy in other jurisdictions or whether such regions require their own strong ZEV policy. I use a vehicle choice model of the North American passenger vehicle sector (modeling the U.S. and Canada) to explore a case study of British Columbia in the context of the ZEV States' ZEV mandate. The model is designed to account for separate regional and global adoption barriers and simulate the effects of regional spillovers. I include scenarios with corporate average fuel economy (CAFE) standard and low carbon fuel standard (LCFS) policies to evaluate the need for ZEVs when other GHG-focused transportation policies are present. I simulate two CAFE and LCFS stringencies, both of which are stronger than what is currently in place. All policy scenarios also include steadily increasing carbon tax.

In the mid-2000s, the British Columbia government of that period established itself as a leader in climate action. Although it has a carbon tax currently frozen at $30 per tonne of carbon dioxide equivalent, the province may need to consider policies specifically designed to increase ZEV adoption as a complement to this tax in achieving its 2050 GHG target of an 80% reduction below 2007 emission levels (SBC, 2007). Switching from conventional to electric vehicles offers substantial and immediate GHG reduction opportunities due to the province's low carbon electricity system. British Columbia's *Clean Energy Act* ensures this GHG reduction opportunity will continue (SBC, 2010). Furthermore, low electricity rates and high gasoline prices compared to other North American cities offer high potential fuel cost savings for drivers (Axsen et al., 2015). As of 2016, British Columbia has a portfolio of demand-focused ZEV policies in place. These include rebates for vehicles and residential chargers, information campaigns, and investments in public charging infrastructure (New Car Dealers of BC, 2015). British Columbia also passed the legislation required to enact a ZEV mandate, but has not yet implemented it (BC MOE, 2008). Like California, British Columbia vehicles are regulated by a federal CAFE standard while the province regulates fuel GHG emissions with a LCFS (P.C., 2014; SBC, 2008). Despite these policies and the opportunity for fuel cost savings, ZEV adoption has been low compared to other regions with strong climate policy. Since

2011, California has sold seven times as many electric vehicles per capita as British Columbia (California Plug-In Electric Vehicle Collaborative, 2015; Stevens, 2015).[5]

I use a vehicle choice model of the North American passenger vehicle sector to investigate the need for strong ZEV policy in British Columbia. My model borrows functions from the passenger vehicle sector of the CIMS energy economy model (see for details: Bataille et al., 2006; Hourcade et al., 2006; Jaccard, 2009). CIMS has been used to evaluate climate policies across all energy using sectors (e.g. Jaccard et al., 2004, 2003; Mundaca et al., 2010; Murphy and Jaccard, 2011), with some recent research has focused on the passenger vehicle sector (Fox, 2013). Consumers are simulated to make vehicle choices based on financial and intangible costs according to a market share equation. Intangible costs represent the non-financial adoption barriers that limit consumer interest in new vehicle technologies. I run a series of policy simulations and analyze the resulting ZEV adoption, GHG emissions, and the cost-effectiveness of GHG reductions. Given the uncertainties inherent in modelling long-term technological change, I use Monte Carlo analysis to generate probabilistic outputs. Two key model features allow me to account for how one region's ZEV policy may affect ZEV adoption both within and outside that region. The first is the ability to endogenously simulate changes in technology and consumer preferences, which is achieved through two functions in the model. The declining capital cost function approximates economies of scale, learning by doing, and investments in research and development. As adoption of a vehicle technology increases, the declining capital cost function drives down its capital costs across all regions simultaneously. The declining intangible cost function represents the "neighbour effect," whereby consumer preferences for a technology increase as its new vehicle market share increases (Axsen et al., 2009; Mau et al., 2008). The neighbour effect is driven by increased credibility, changes in social concerns, the spread of information about user experiences, education and marketing, shifts in cultural norms, and the need some technologies have for complementary infrastructure (Norton et al., 1998; van der Vooren et al., 2012; Yang and Allenby, 2003).

The second key model feature is the representation of regional and global adoption barriers through separate regional and global intangible cost parameters. Regional

---

[5] Cumulative electric vehicle sales as of June 2015: BC = 2370, California = 142,069.
Population as of 2014: BC = 4.631 million, California = 38.8 million.

intangible costs in the model are unique to each region (e.g. representing availability of public charging infrastructure), whereas global intangible costs are the same across all regions (e.g. representing increased vehicle electric driving range or improvements in other metrics of battery performance). Through the declining intangible cost function, regional intangible costs decline as a technology's regional market share increases, and global intangible costs decline as a technology's total market share increases across all regions. As a result, governments have the opportunity to free-ride off ZEV policy in other regions. For example, a pro-ZEV policy in California will increase BEV market share in that state, which increases overall BEV market share across all regions. This, in turn, decreases global BEV intangible costs in all regions and may thus increase BEV market share in regions other than California. The same process applies to the others ZEVs as well (PHEVs and HFCVs).

In summary, my research objectives are as follows:

1. Simulate the spillover effects of California's ZEV mandate in a small North American region (the case of British Columbia).
2. Determine if British Columbia needs strong ZEV policy to achieve its 2050 GHG target.
3. Analyze how the cost-effectiveness of GHG reductions in British Columbia is affected by increasing levels of ZEV adoption in other jurisdictions.

I assume that British Columbia must achieve an 80% GHG emissions reduction in the passenger vehicle sector to achieve its economy-wide GHG target of 80% below 2007 levels by 2050. The actual emissions reductions that are needed from passenger vehicles could be higher or lower, depending in particular on the cost-effectiveness of GHG reductions in the passenger vehicle sector compared to other sectors.

Chapter 2.

Methods

2.1. Model overview

To pursue my research objectives, I simulate policy scenarios using an Excel-based vehicle choice model of the North American passenger vehicle sector. The model is adapted from the CIMS energy economy model and calibrated to the *Reference Case* of the U.S Energy Information Administration's (EIA) *Annual Energy Outlook 2014* (*AEO2014*) (U.S. EIA, 2014). I calibrated the model by adjusting vehicle technology capital and intangible costs until my model's to align with the *AEO2014 Reference Case's* tailpipe GHG emissions, vehicle technology market shares, and total vehicle demand (measured in vehicle kilometres travelled, VKT). The model simulates the composition, costs, and GHG impacts of the passenger vehicle sector in five year periods between 2005 and 2050. During each period, a heterogeneous consumer market determines the market shares of a set of vehicle technologies. Consumers choose vehicle technologies to purchase based on relative financial and intangible costs. As introduced in section 1.5, intangible costs represent the influence that non-financial adoption barriers have on consumer purchase decisions. As a simulation progresses, emerging technologies can become more attractive through endogenous functions that drive down capital and intangible costs. Table 1 provides an overview of the model inputs, outputs, and key functions.

I make four modifications to the conventional CIMS model architecture that help me achieve my research objectives. First, I split the model into four interdependent regions. Second, I used the @Risk add-on for Excel and the Monte Carlo method to explicitly account for uncertainty in my input parameters. I detail both of these modifications in the next two paragraphs. Third, I separated intangible costs into regional and global components to better account for the fact that adoption barriers are affected by developments occurring both within and outside a given region (see section 2.4). Finally, I expanded the declining capital cost function to more explicitly account for vehicle demand growth and potential ZEV sales outside North America see section 2.3). In focusing my model on one sector of CIMS, I replace CIMS' endogenous fuel supply sector with exogenous price and GHG intensity schedules (see section 2.7). I discuss this and other methods limitations in section 4.6.

The model is composed of four interdependent regions–British Columbia, the Rest of Canada, the ZEV States (California, Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont and the Rest of the United States (U.S.). Capital costs decline based on a technology's cumulative vehicle production from all regions (described in section 2.3), and each region experiences the capital cost declines simultaneously. Intangible costs decline based on a technology's market share. Regional intangible costs decline as the technology's regional market share increases and are thus unique to each region. Global intangible costs decline as the technology's market share across all four regions increases and are shared by all regions. As such, the capital and intangible costs facing a region's consumers depend on developments both within and outside the region. Larger regions will have a larger impact on capital and global intangible cost declines. Table 1 summarizes the relative market size of each region.

As noted in other recent ZEV modelling studies, projecting long-term technological change and market responses to new technologies involves a high degree of uncertainty (e.g. Greene et al., 2014a, 2014b). Quantifying this uncertainty can help policymakers understand potential challenges in facilitating a transition to sustainable vehicles and fuels (Bastani et al., 2012), including identifying the variables to which GHG reductions and ZEV adoption are most sensitive. For this study, I quantify uncertainty using Monte Carlo analysis. Monte Carlo analysis involves assigning probability distributions to all uncertain input parameters and running each simulation through multiple iterations (Morgan and Henrion, 1990). During each iteration, the model randomly selects a value for each uncertain input based on its probability distribution. I ran each simulation through 1000 iterations, resulting in probability distributions for each output comprised of 1000 data points. I then conducted sensitivity analysis to identify which inputs have the largest impact on my results. This sort of analysis helps provide insight into what variables and assumptions affect the key model outputs, but does not address all uncertainty in the model because, for example, there is still uncertainty regarding the characteristics of the Monte Carlo distributions I assign.

Table 1 Overview of the model

<table>
<tr><th>Exogenous inputs</th><th>Key functions</th><th>Outputs</th></tr>
<tr><td rowspan="3">Vehicle kilometers travelled (VKT) demand growth rate
Vehicle financial and intangible costs
Regional-global intangible cost split
Vehicle fuel efficiency attributes
Vehicle retirement rates
Energy/fuel prices
Energy/fuel GHG emissions factors
Declining capital cost parameters
Declining intangible cost parameters
Purchase behaviour parameters
Vehicle and VKT demand elasticities
Policies
Monte Carlo uncertainty distributions</td><td>Market share competition
Declining capital cost function
Declining intangible cost function
Vehicle and VKT demand feedback functions (policy scenarios only)</td><td>Vehicle technology market shares and total stock
Well-to-wheel GHG emissions
Abatement costs</td></tr>
<tr><th colspan="2">Regional proportion of North American (U.S. and Canada) passenger vehicle demand market</th></tr>
<tr><td colspan="2">British Columbia: 0.7%
ZEV States: 23.2%
Rest of Canada: 6.5%
Rest of the United States: 69.6%</td></tr>
</table>

2.2. Vehicle technology market share competition

Total passenger vehicle demand is based on an exogenous VKT forecast from *AEO2014* (U.S. EIA, 2014). To account for uncertainty in this forecast, I assign a Monte Carlo uncertainty distribution to annual VKT demand growth (Table 2) and allow VKT demand to fluctuate for a given region based on historical demand. For example, Canada's VKT demand varies between 6% and 8% of U.S. VKT demand in any given period. This allows me to capture the effects of regional differences in VKT demand growth that can occur naturally or as a result of differences in regional transportation policies (e.g. increased public transit).

Seven vehicle technologies—gasoline, diesel, ethanol, hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), battery electric vehicle (BEV), and hydrogen fuel cell vehicle (HFCV)—compete to satisfy projected VKT demand in two markets. First, VKT demand is satisfied by an existing vehicle stock. The existing vehicle stock includes vehicles that were purchased in earlier periods of a simulation and have not yet been retired. Vehicles are retired according to U.S. National Highway Traffic Safety Administration rates: 10% after 5 years, 35% after 10 years, 70% after 15 years, and 100% after 20 years (Lu, 2006). Once the existing vehicle stock has satisfied as much of a period's total VKT demand as it can, passenger vehicle technologies compete for a share of the new vehicle market.

New vehicle market share is determined by a heterogeneous consumer market that purchases vehicles according to a market share competition:

$$MS_j = \frac{LCC_j^{-v}}{\sum_{k=1}^{K}\{LCC_K^{-v}\}} \qquad \text{(Equation 1)}$$

Equation 1 allocates new vehicle market share based on each technology's lifecycle costs (*LCC_j*) compared to the lifecycle costs of all available technologies (*LCC_K*). I describe lifecycle costs in the paragraph below. A behavioural parameter termed market heterogeneity (*v*) defines the degree to which consumers perceive varying lifecycle costs for the same technology. A higher *v* leads the technology with the lowest lifecycle cost to capture a higher market share, whereas a lower *v* reduces the importance of differences in lifecycle costs and allocates market share more evenly among competing technologies (Bataille et al., 2006). A more detailed overview of the market heterogeneity parameter can be found in Rivers and Jaccard (2005).

A vehicle's lifecycle cost includes all financial and intangible costs expected over anticipated lifespan of the vehicle:

$$LCC_j = \left[\left(CC_j + i_j\right) * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j\right] \qquad \text{(Equation 2)}$$

The lifecycle cost of a technology (*LCC_j*) includes its upfront capital cost (*CC_j*), upfront intangible cost (*i_j*), annual maintenance cost (*MC_j*), and annual energy cost (*EC_j*). Equation 2 annualizes upfront capital and intangible costs to spread them over the anticipated life of the vehicle (*n_j* = 15 years) according to a private discount rate (*r*). The private discount rate (Table 2) is a behavioural parameter that determines how consumers perceive future costs (Train, 1985). The higher the value of *r*, the more consumers value near-term costs and benefits over future costs and benefits.

To better understand how market share is allocated between vehicle technologies, consider the example of consumers choosing between a gasoline vehicle and a BEV. In this case, the BEV has lower fuel costs, but has higher capital and intangible costs, and overall will have a higher lifecycle cost the gasoline vehicle. As such, consumers buy more gasoline vehicles than BEVs. The more costly BEV still receives some market share due to the influence of the market heterogeneity parameter (e.g. where some segment of consumers may be less cost sensitive and have uniquely high valuation of a BEV). As BEV production and sales increase, the model's declining cost functions will cause BEV capital and intangible costs to decline (as described in sections 2.2 and 2.3). As such, the incremental price premium to purchase a BEV (relative to a conventional gasoline vehicle) will decrease and BEVs will become more attractive to a larger number of consumers.

Table 2 Vehicle demand parameters

Vehicle demand parameters	Source	Uniform Uncertainty Distribution	
		Minimum	Maximum
VKT annual growth rate	U.S. EIA, 2014	0.75%	1.05%
Private discount rate (r)	Axsen et al., 2009; Horne et al., 2005; Mau et al., 2008	21.5%	28.5%
Market heterogeneity (v)		7	13

2.3. Declining capital costs: endogenous technological change

The model represents endogenous technological change through a declining capital cost function. Capital costs decline for four of the emerging technologies–HEVs, PHEVs, BEVs, and HFCVs–as the production of each technology increases:

$$CC_j(t) = CC_j(t_0)\left(\frac{N_j(t)}{N_j(t_0)}\right)^{\log_2 PR_j} \qquad \text{(Equation 3)}$$

Each emerging technology's capital cost (CC_j) declines based on its progress ratio (PR_j) until the technology reaches maturity (defined by a minimum capital cost) (Jaccard, 2009). The progress ratio defines the rate at which capital costs decline every time a technology's cumulative production (N_j) doubles (N_j in time t vs. N_j in time t_0). I take progress ratios from recent empirical estimates of vehicle cost declines (Nykvist and Nilsson, 2015; Weiss et al., 2012). The progress ratios capture multiple technological change processes, including learning by doing, whereby firms achieve cost reductions as they gain production experience, economies of scale, whereby firms achieve cost reductions as a result of moving to larger scale production, and research and development. Table 3 summarizes each vehicle's capital cost values and the progress ratios of emerging technologies. As in previous CIMS-based modelling studies, I group HEVs, PHEVs, and BEVs into a technology class of "battery vehicles" and set the capital costs of each of them to decline based on the cumulative production of all of them (e.g. Fox, 2013).

Table 3 Vehicle technology capital cost (*CC*) parameters

Vehicle tech.	Initial *CC* in 2005 (CAD2005)*		*CC* at maturity (% of initial)		Progress ratio		Exogenous annual *CC* decline rate***		Example total *CC* in Reference Case	
	min.**	max.	min.	max.	min.	max.	min.	max.	2015	2020
Gasoline	$5800		-	-	-	-	-	-	$31783	$31783
Diesel	$8480	$10880	-	-	-	-	-	-	$35663	$35663
Ethanol	$4800	$7200	-	-	-	-	-	-	$31983	$31983
HEV	$18005	$20405	22%	42%	0.89	0.97	0.0%	1.0%	$42301	$40519
PHEV	$41025	$43425	12%	32%	0.85	0.93	0.5%	1.5%	$57844	$52183
BEV	$45593	$47993	10%	14%	0.83	0.91	0.5%	1.5%	$60065	$53226
HFCV	$180300	$182700	4%	10%	0.72	0.88	2.5%	7.5%	$134654	$83074

*Vehicle body costs are the same for all vehicle technologies and remain static throughout the simulation period. Body costs have a normal uncertainty distribution with a mean value of $25983 and a standard deviation of $1000.

**Parameters are assigned uniform uncertainty distributions with the minimum and maximum values in the table.

***The exogenous annual capital cost decline rate determines the decline in capital cost that occurs over time for a vehicle technology regardless of cumulative production.

Sources:

Initial CC and CC at maturity: Based on sources used to populate the full CIMS model and adjusted in calibrating the reference case to AEO2014: Bandivadekar et al., 2008; EU Powertrain Coalition and McKinsey & Company, 2010; Kalhammer et al., 2007; Kromer and Heywood, 2007; Offer et al., 2010; U.S. EIA, 2014

Progress ratios for HEV, PHEV, and BEV: Nykvist and Nilsson, 2015; Weiss et al., 2012

Progress ratio for HFCV: IEA, 2007; Schoots et al., 2010

Exogenous annual CC decline: Bandivadekar et al., 2008; EU Powertrain Coalition and McKinsey & Company, 2010; Kalhammer et al., 2007; Kromer and Heywood, 2007; NRC, 2013; Offer et al., 2010

To account for the effects of ZEV adoption outside the model's four regions, I use a cumulative production parameter (N_j) that includes vehicle sales in both North America and the rest of the world (measured in VKT). I took each vehicle's initial production(N_j in time t_0, 2005) for North America from the Fox (2013) and used the values to calculate initial ZEV production in the rest of the world. Approximately 60% of global ZEV sales through 2014 occurred outside North America (ZSW, 2015), with the remaining 40% in North America.

$$N_j = N_{NAj} + N_{RoWj} \qquad \textbf{(}\text{Equation 4)}$$

During each simulation period, the North American production of each vehicle technology (N_{NAj}) is endogenously determined based on sales allocated by the model's market share competition (Equation 1). The model then calculates sales (i.e. production) of each vehicle technology in the rest of the world (N_{RoWj}) based on two assumptions. First, I assume total VKT demand grows 5% faster in the rest of the world than in North America (based on Dargay et al., 2007). Second, I use an uncertainty distribution to determine ZEV production (equal to sales) in the rest of the world based on the growth of ZEV production in North America. I thus assume that the stringency of ZEV policies globally will be positively correlated with the stringency of the overall ZEV policies implemented in North America in a given policy simulation. I assign a uniform uncertainty distribution that grows ZEV production in the rest of the world at 80% to 120% of the rate ZEV production grows in North America. Thus, for example, if North American BEV production grows 10% in one period, the model uses the Monte Carlo method to run 1000 iterations where ZEV production in the rest of the world grow by 8% to 12%.

2.4. Declining intangible costs: shifts in adoption barriers and consumer preferences

Intangible costs represent non-financial adoption barriers that affect, or limit, consumer interest in purchasing a vehicle technology. Intangible costs are estimates of consumer perceptions and preferences regarding the quality, reliability, availability, and social desirability of new technologies. These estimates have been derived through revealed and stated preference methods that seek to quantify the effect of these consumer perceptions and preferences on purchase decisions (Axsen et al., 2009; Rivers and Jaccard, 2006). A vehicle technology's intangible cost (i_j) consists of a fixed (i_{Fj}) and variable (i_{Vj}) portion. Fixed intangible costs represent observed patterns in consumer preferences that seem to be permanent despite the widespread availability of a given technology (e.g. North American consumers' preference for gasoline over diesel vehicles). Variable intangible costs represent non-financial adoption barriers that decline as a technology becomes more widespread, i.e. as its market share increases. This process is captured in a declining intangible cost function.

The declining intangible cost function is based on the “neighbour effect”, in which an increase in the prevalence of a given technology causes a reduction in the influence of non-financial adoption barriers (Axsen et al., 2009; Mau et al., 2008):

$$i_{Vj}(t) = \frac{i_{Vj}(t_0)}{1 + Ae^{k*MS_j(t-1)}} \qquad \text{(Equation 5)}$$

Where the variable intangible cost (i_{Vj}) of a given technology in time t depends on its initial variable intangible cost (i_{Vj} in time t_0), its market share in the previous period (MS_j in time $t-1$), and two behavioural parameters (A and k). A and k have fixed values that define the shape of the intangible cost curve and the rate at which intangible costs decline from an increase in market share, respectively (A = 0.0065 and k = 40) (Axsen et al., 2009; Mau et al., 2008). In my model, all vehicle technologies except gasoline vehicles experience intangible cost declines. Similar to the declining capital cost function, I group BEVs and PHEVs into a technology class, where the intangible cost of one vehicle technology depends partially on market share increases achieved by the other. As with the declining capital cost function, variable intangible costs decline until the vehicles reach maturity, as represented by a minimum variable intangible cost parameter. Table 4 summarizes the intangible cost parameter values for each vehicle technology. I based these values on studies that use and develop empirical methods to estimate intangible cost parameter values for the full CIMS model (Axsen et al., 2009; Horne et al., 2005; Mau et al., 2008).

Table 4 Vehicle technology intangible cost (*i*) parameters

Vehicle technology	Fixed *i* (CAD2005)		Initial variable *i* in 2005 (CAD2005)		Variable *i* at maturity (% of initial)	
	min.*	max.	min.	max.	min.	max.
Gasoline	-$2500		-	-	-	-
Diesel	$2900	$4100	$4840	$6040	10%	20%
Ethanol	-$150	$1050	$150	$1350	16%	26%
HEV	-$600	$600	$5275	$6475	0%	10%
PHEV	-$100	$1100	$12900	$14100	0%	12%
BEV	$250	$1450	$14400	$15600	0%	12%
HFCV	$1350	$2250	$26900	$28900	0%	12%

*Parameters are assigned uniform uncertainty distributions with the minimum and maximum values in the table.

Sources:

Based on sources used to populate the full CIMS model and adjusted in calibrating the reference case to *AEO2014*: Axsen et al., 2009; Horne et al., 2005; Mau et al., 2008; U.S. EIA, 2014

Recall from section 1.1 that the influence that adoption barriers have on a region's level of ZEV adoption depends on developments occurring both within and outside the region (Lutsey et al., 2015). Therefore, as introduced in section 1.5, I split variable intangible costs into regional and global components and incorporated a unique declining intangible cost function for each component. In each declining intangible cost function, I replace the generic i_{Vj} and MS_j parameters in Equation 5 with their respective regional or global parameters. As such, a vehicle technology's regional intangible cost declines as its regional market share increases, whereas its global intangible cost declines as its market share increases across all four regions. A vehicle technology's global intangible cost will always be the same for all regions, whereas its regional intangible cost will be unique to each region. Thus, for example, total BEV intangible costs in British Columbia will be the sum of a fixed component, a global variable component that is the same across all regions, and a regional variable component that is unique to British Columbia, and thus completely dependent on adoption levels in the province.

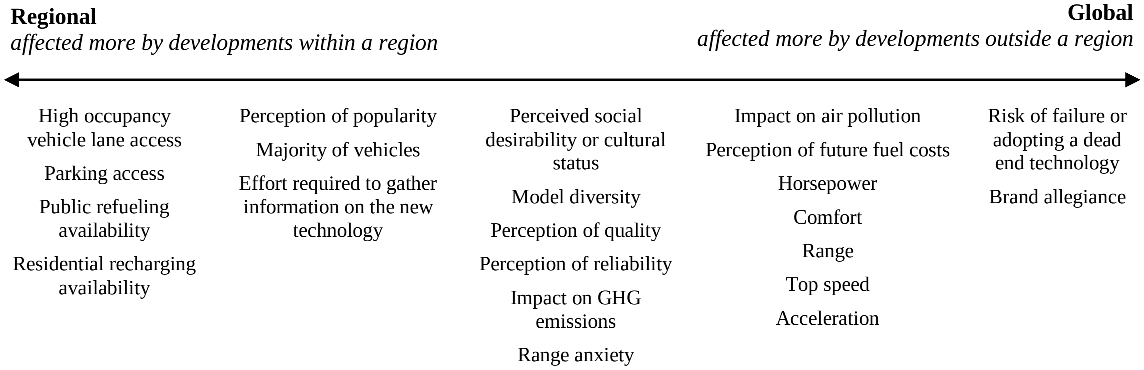
For each declining intangible cost function to work, I needed to determine how to split initial variable intangible costs (i_{Vj} in time t_0) into regional and global components. I discuss the literature review process I undertook to accomplish that in the following section.

2.5. The regional-global intangible cost split

To determine the regional-global split to apply to initial variable intangible costs, I reviewed modelling and survey-based studies that have quantified the effect non-financial adoption barriers have on vehicle purchase decisions. Table A.1 in the Appendix lists the studies I reviewed and parameters each study includes.

My literature review involved two stages. In the first stage, I started by determining which non-financial factors to include and classified each factor based on whether its impact on purchase decisions depends more on developments within or outside a region. I included all factors from modelling studies and factors found to have a statistically significant influence on purchase decisions from survey-based studies. I classified each factor along a regional-global continuum based on how they were discussed in this and other literature, as well as my own personal judgment. Figure 1 presents an abstract version of the resulting continuum with components grouped according to their general position. For example, I placed range anxiety close to the midpoint of the continuum because it depends on both battery range and the availability of public charging stations. The positioning is subjective by nature, and simplifies the complexity of these various barriers. Range anxiety will also be affected by things like word of mouth and the experiences and perspectives of people and organizations a consumer trusts. However, this sort of simplification was necessary to stay within the scope of this novel modelling exercise. As discussed at the end of this section, I use Monte Carlo simulations to better understand how different variables and my assumptions affect my key results.

Figure 1 Regional-global intangible cost continuum



Note: The intangible cost components listed on this continuum are based on the literature summarized in Table A.1 in the Appendix.

The second stage of my literature review involved quantifying the relative influence that each non-financial factor has on purchase decisions. Each study I reviewed includes a different set of non-financial factors, and the same factors influence purchase decisions differently in different modelling studies (e.g. by defining the vehicle choice set versus by increasing the cost of vehicles in the choice set). As such, I did not take specific quantitative values from any study. Rather, I again placed each factor from each study along a continuum based on its influence on purchase decisions relative to other factors in the study. The same factor could be classified in multiple ways based on how they were treated in different studies; for example, in comparing 17 studies, battery range had a 'small' influence in five studies, a 'medium-large' influence in five other studies, and a variety of other levels of influence in the remaining seven studies. I ultimately positioned each factor on the continuum according to its average classification and the ways it was discussed in each study. Again, this process required personal judgment.

Combining the results of the two stages described above, I arrived at an intangible cost split of 50% regional and 50% global. However, as noted in some of the studies I reviewed, our current capacity to quantify the types of factors I include in intangible costs is still limited (e.g. Greene et al., 2014a). Researchers report that it is difficult to disentangle consumer preferences into discrete attributes (Axsen et al., 2009; van der Vooren and Brouillat, 2013). Additionally, consumers have different and dynamic perspectives and values regarding features like charge time and driving range (Bočkarjova et al., 2014). Given the high degree of uncertainty in my novel approach and these parameters in general, I assigned the 50/50 split a 15% standard deviation for use in my Monte Carlo simulations. As such, 68% of iterations involve variable intangible costs being weighted between 35% regional, 65% global and 65% regional, 35% global. Furthermore, I conduct sensitivity analyses to better understand how my main results are affected by the full range of possible intangible cost splits–from 100% regional to 100% global.

2.6. Feedback effects

Simulating policies in my model can cause changes to prices and fuel efficiencies that affect the costs consumers experience relative to the reference case. In response to these changes in costs (*C*), consumers are expected to adjust their level of VKT demand

(*D*), which in the market for new vehicles is translated to vehicle demand. If costs increase, demand is expected to decrease, and vice versa. The change in demand depends on an elasticity parameter (*e*) that defines how sensitive consumers are to changes in cost. For every 1% increase in average costs, we expect an *e*% decrease in demand, and vice versa. Elasticity equations act on both of the model's markets: the market for new vehicles and the market for VKT from existing vehicles. –I use the following equation:

$$D_{POL}(t) = D_{REF}(t) \times e \times \frac{(\sum C_{jREF}\, x\, MS_{jREF} - \sum C_{jPOL}\, x\, MS_{jPOL})}{\sum C_{jREF}\, x\, MS_{jREF}} \qquad \text{(Equation 6)}$$

Using Equation 6, demand in the policy scenario (D_{POL}) is the product of demand in the reference case (D_{REF}), the elasticity parameter (*e*), and the percentage change in average cost per VKT in each market.

In the market for new vehicles, consumers respond to changes in capital costs. The elasticity parameter has a uniform uncertainty distribution between -0.5 and -0.6, based on vehicle price elasticities found for passenger vehicle travel in the United Kingdom in 2010 (Fouquet, 2012). Therefore, for every 1% increase in the average capital cost of new vehicles, the demand for new vehicles will decrease by 0.5% to 0.6%.

In the market for VKT from existing vehicles, consumers respond to changes in the cost of driving, i.e. energy and maintenance costs. Including energy costs means this equation captures the rebound effect, whereby drivers may increase VKT demand as increases in fuel efficiency decrease energy costs (Hymel et al., 2010). The elasticity in this market has a uniform uncertainty distribution between -0.15 and -0.25, based on fuel price elasticities found for passenger vehicle travel in the United States up to 2001 (Small and Van Dender, 2007). Therefore, a 1% increase in average driving costs in a policy scenario leads to a 0.15% to 0.25% decrease in VKT demand from existing vehicles (this does not affect new vehicle demand).

2.7. Energy price and GHG assumptions

The model includes five fuels: gasoline, diesel, ethanol, hydrogen, and electricity. Each fuel is defined by a set of exogenous price and GHG intensity schedules. This means that fuel prices are predetermined, and are not affected by changes in fuel demand (i.e. the model is not a full equilibrium model). As described below, these schedules interacts with other model parameters to determine energy costs and GHG emissions during each model period.

Energy costs in each period are a product of vehicle fuel efficiency, VKT demand, and energy prices. Vehicle fuel efficiency depends on a region's corporate average fuel economy (CAFE) standard, which I describe in section 2.9. I assume all vehicle technologies satisfy 20,000 km of VKT demand each year. Gasoline, diesel, and ethanol price schedules are based on NRC's (2013) forecasts to 2050, while hydrogen prices were taken from a previous CIMS-based ZEV modelling study (Fox, 2013). I assigned a normal uncertainty distribution with a standard deviation of 20% to future gasoline, diesel, ethanol, and hydrogen prices to capture the effect of future energy price fluctuations. Gasoline, diesel, and ethanol prices are unique to each region, but the relative prices between regions are linked in stochastic Monte Carlo relationships. For example, gasoline is always approximately 7% more expensive in British Columbia than the Rest of Canada. If the price of gasoline increases by 10% in the Rest of Canada, it also increases by 10% in British Columbia, and gasoline remains approximately 7% more expensive in British Columbia than in the Rest of Canada. This process accounts for the fact that fuel prices differ between regions, but price fluctuations are primarily driven by global energy markets. Regional price relationships are based on historical price data.[6] Hydrogen fuel has a limited price history so I assume prices are the same in all regions. In British Columbia, a carbon tax increases the price of any fuels that result in GHG emissions.

Electricity prices are unique to each region and depend on whether the region follows a low carbon electricity path or not. These two price trajectories are based on the price trajectories used in NRC's (2013) reference case and low carbon electricity price scenarios. I assume British Columbia remains on a low carbon trajectory, starting at BC Hydro's 2015 rate (Province of British Columbia, 2014). I assign future electricity prices a normal uncertainty distribution with a standard deviation of 10%. Table 5 presents British Columbia's mean fuel price schedule for each fuel.

---

[6] Historical price data comes from the U.S. Energy Information Administration, U.S. Department of Energy's Alternative Fuels Data Center, Natural Resources Canada, and GasBuddy.com.

Table 5 Mean fuel price schedule for British Columbia (CAD2005/GJ)

Fuel	Mean Fuel Price								Standard Deviation (% of mean price)
	2015	2020	2025	2030	2035	2040	2045	2050	
Gasoline	37.17	40.94	43.22	44.80	45.69	46.37	46.76	46.76	20%
Diesel	30.40	30.40	35.94	39.59	41.79	43.31	44.18	44.83	20%
Ethanol	54.68	54.68	61.92	69.16	71.74	74.32	76.90	76.90	20%
Hydrogen	55.59	46.64	45.19	42.68	42.68	42.68	42.68	42.68	20%
Electricity	24.91	24.91	24.91	26.16	27.40	28.65	29.89	31.14	10%

Sources:
Gasoline, Diesel, and Ethanol: NRC, 2013
Hydrogen: Fox, 2013
Electricity: Starting based on Province of British Columbia, 2014 and following the low carbon trajectory from NRC, 2013

A vehicle's GHG emissions depends on its fuel efficiency and the well-to-wheel GHG intensity of the fuel or fuels it uses. I track well-to-wheel (WTW) GHG emissions to capture the GHGs emitted in the process of producing a fuel and transporting it to the point at which is enters a vehicle for consumption. Electricity and hydrogen have zero tailpipe GHG emissions, but can have high WTW GHG emissions if their fuel is produced with high carbon energy sources. WTW emissions thus provide a more realistic assessment of the GHG impacts of shifting to ZEVs. With the exception of electricity, the WTW GHG intensity of each fuel in the model depends on whether a region has implemented a low carbon fuel standard (LCFS) and at what stringency (described alongside other policies in section 2.9). The WTW GHG intensity of a region's electricity depends on whether it follows a reference or low carbon case.[7] I assume British Columbia stays on a low carbon trajectory based on the Province's *Clean Energy Act* (SBC, 2010). The well-to-wheel GHG intensity (based on LCFS stringency) and fuel efficiency (based on CAFE standard stringency) schedules for each fuel and vehicle are included in the Appendix.

---

[7] The WTW GHG intensity of electricity can be affected by the LCFS, but in this case is assumed to follow a low carbon trajectory that brings the GHG intensity below the level required by the LCFS.

2.8. Calculating abatement costs

Each time I run a policy simulation, the model calculates the abatement cost of any GHG reductions achieved by the policy relative to a reference case. I report GHG abatement costs using a cost-effectiveness value calculated as the cost per tonne of WTW GHG emissions reduced over an entire simulation (CAD2015 per tonne carbon dioxide equivalent, tCO2e). The higher the cost-effectiveness value, the less cost-effective the policies are at reducing GHG emissions, and vice versa. I use the three abatement cost measures described below. The abatement cost measures account for private costs only (i.e. those experienced directly by drivers), and do not account for public costs or benefits (e.g. from reduced air pollution).

The first cost measure includes only financial costs. Financial costs account for differences in consumer spending on lifecycle capital, energy, and maintenance costs between the policy simulation and reference case in each period. Any future energy and maintenance costs are discounted to the current period using a social discount rate of 5% (Peters, 2006), which represents society's perception of future costs (Small, 2012). From an economic perspective, the financial cost measure assumes technologies that provide the same energy service are perceived by consumers as perfect substitutes (Hourcade et al., 2006; Jaccard, 2009; Murphy and Jaccard, 2011). As a result, the financial cost measure tends to underestimate the costs consumers experience as a result of a policy.

The perceived cost measure is designed to better capture consumer behaviour patterns that result because of consumer perceptions that technologies are imperfect substitutes for one another (Murphy and Jaccard, 2011). In addition to capital, maintenance, and energy costs, the perceived cost measure includes intangible costs. Where the financial cost measure uses a 5% social discount rate to represent the value of future costs to society, the perceived cost measure discounts future costs using a higher private discount rate of 25% that represents the value of future costs to individuals (see Table 1 for Monte Carlo distributions). A more detailed overview of the perceived cost calculations can be found in Peters (2006) or Fox (2013). Where the financial measure tends to underestimate abatement costs, the perceived cost measure tends to overestimate abatement costs. The perceived cost measure overestimates costs because it assumes that consumer choices in the reference case are optimal, and therefore any deviation from the reference case decreases consumer welfare. In doing so, the perceived cost measure ignores research that shows regulations can increase consumer welfare (Moxnes, 2004) and that people's technology preferences can change over time (Duke and Kammen, 1999).

The third abatement cost measure is designed to account for the influence of consumer perceptions missing from the financial cost measure, while not overstating the optimality of consumers' choices in the reference case, as is done with the perceived cost measure. I call this measure CIMS midpoint costs. The model calculates the CIMS midpoint cost measure using a weighting factor (*w*) to find a midpoint between the financial and perceived cost measures:

$$CIMS\ Midpoint\ Costs = Financial\ Costs + \left((Perceived\ Costs - Financial\ Costs) * w\right)$$

(Equation 7)

I assign *w* a uniform Monte Carlo uncertainty distribution between 0.7 and 0.8. This value is based on the judgment in Fox (2013) that approximately 25% of perceived costs are the product of market failures and bounded rationality. Fox (2013) note that the weighting factor value lacks a strong empirical base, so I present the financial and perceived cost measures in addition to CIMS midpoint costs. Once calculated for each period, all abatement cost measures are discounted to CAD2015 using the social discount rate of 5%.

2.9. Policy simulations and assumptions

I simulated a reference case and a series of policy scenarios designed to help me achieve my three research objectives. My reference case is intended to approximate the current policy environment and is calibrated to *AEO2014's Reference Case* (U.S. EIA, 2014). I calibrated the model based on tailpipe GHG emissions, vehicle technology market shares, and total VKT demand in the U.S. regions. I achieved calibration by making small adjustments to my capital and intangible cost parameters.

The policy scenarios I simulated for each objective were designed to build on the primary results of the simulations run for the previous objective. I analyzed each simulation by focusing on a combination of three outputs:

- ZEV adoption: This is equal to the total new vehicle market share of BEVs, PHEVs, and HFCVs.
- WTW GHG reductions: I assume emissions must decline 80% by 2050 in the passenger vehicle sector for British Columbia to achieve its overall GHG target (80% reductions relative to 2007) (SBC, 2007).
- Abatement costs: These are calculated using the three cost-effectiveness measures described in section 2.8.

I simulate five different policies in various combinations to achieve my objectives: a ZEV mandate, the vehicle fuel efficiency standard, fuel GHG intensity standard, a carbon tax, and vehicle purchase subsidies. Table 6 provides a summary of each policy simulation and the reference case.

The ZEV mandate in this study requires ZEVs to reach a minimum percentage of new vehicle market share in each period according to one of three stringency schedules (Table 7). The market share requirement can be met by any combination of BEVs, PHEVs, and HFCVs. The reference case scenario is similar to California's existing mandate, except that California's mandate forces increasing numbers of BEVs and HFCVs over time by decreasing the market share requirement that can be met by PHEVs (CCR, 2015).

British Columbia also implements a carbon tax in each scenario. In the reference case, the carbon tax is kept frozen at its current level of $30 per tonne carbon dioxide equivalent (Table 7). For policy simulations, I assume British Columbia's carbon tax steadily rises to reach $118 per tonne by 2050. No other regions implement a carbon tax.

Table 6 **Overview of simulations for each research objective**

Scenario	Description of simulations and analyses
Reference case	All regions implement a reference case CAFE standard until 2025, while British Columbia and the ZEV States implement a reference case LCFS until 2020. British Columbia maintains its $30 carbon tax on fossil fuel combustion until 2050 (BC MOF, 2015). I assume the ZEV States maintain the reference case ZEV mandate at the 2025 stringency until 2050. I analyze ZEV adoption and WTW GHG reductions relative to the 2050 target.
Objective 1	I run two simulations where the ZEV States increase the stringency of their ZEV mandate; first to medium stringency, then to high stringency. All other policies remain in the reference case scenario. For both simulations, I analyze how ZEV adoption and GHG reductions in British Columbia change in response to the resulting increases in ZEV adoption in the ZEV States.
Objective 2	I run a series of simulations to estimate the probability that British Columbia can achieve its 2050 GHG target without stronger ZEV policies. British Columbia implements two CAFE and LCFS policy packages; first at medium stringency, then at high stringency. Both packages also include a higher carbon tax and $5000 purchase subsidy on ZEVs until 2020. The ZEV States maintain their high stringency ZEV mandate from Objective 1. For each package, I determine what percentage of iterations achieve the 2050 GHG target. If the policy package does not hit the GHG target in 80% of the Monte Carlo iterations, I determine the stringency of the additional ZEV mandate British Columbia would need to implement to have an 80% chance of achieving its 2050 GHG target.
Objective 3	Building on Objective 2, British Columbia maintains the medium stringency CAFE and LCFS package with the ZEV mandate required to have an 80% change of achieving its 2050 GHG target. The ZEV States maintain a high stringency ZEV mandate. I calculate the cost-effectiveness of achieved GHG reductions. Then, I run additional simulations to investigate how the cost-effectiveness of GHG reductions in British Columbia changes as other regions adopt ZEV mandates. The other regions implement medium stringency ZEV mandates as follows: the Rest of Canada in 2020, the rest of North America in 2020, the Rest of Canada in 2025, and the rest of North America in 2025. The ZEV mandates in these regions start at the stringency they would have started at in 2015 and increase at the rate shown in Table 7.

Table 7 **ZEV mandate and British Columbia carbon tax stringencies**

Policy	Stringency	2015	2020	2025	2030	2035	2040	2045	2050
ZEV mandate *minimum new vehicle market share*	Reference case	3%	7%	15.5%	15.5%	15.5%	15.5%	15.5%	15.5%
	Medium	3%	12%	20%	25%	35%	45%	55%	65%
	High	3%	14%	25%	30%	40%	60%	80%	100%
Carbon tax *$/tCO_2e$ (CAD2005)*	Reference case	$30	$30	$30	$30	$30	$30	$30	$30
	Policy packages	$30	$43	$55	$68	$80	$93	$105	$118

Two other policies play an especially important role in the simulations: the corporate average fuel economy (CAFE) standard and the low carbon fuel standard (LCFS). CAFE requires automakers to decrease the average GHG intensity and increase the average fuel economy of their vehicle fleets (CFR, 2012), LCFS requires fuel suppliers to reduce the carbon intensity of their fuels (CCR, 2010; SBC, 2008). I represent both policies using exogenous technological improvements and shadow prices. For CAFE, the fuel economy of each vehicle technology improves while a shadow price increases the capital cost of all vehicles based on their relative fuel efficiency ($/GJ/km). The shadow price makes less fuel efficient vehicles more costly and thus less attractive to consumers. For LCFS, the WTW GHG intensity of each fuel decreases while a shadow price adds a surcharge to fuels based on their relative WTW GHG intensity ($/t$CO_2$e/GJ). The shadow price increases the cost of more polluting fuels. I determined the shadow prices by calibrating the policies to *AEO2014*'s *Extended Policies* case (U.S. EIA, 2014).

I simulate three CAFE and LCFS policy stringencies (summarized in Tables A.2 and A.3 in the Appendix). The reference case stringencies replicate North America's existing policy situation (as modelled in U.S. EIA, 2014). CAFE is implemented across North America until it sunsets in 2025, while LCFS is implemented in British Columbia and the ZEV States until 2020.[8] The medium and high stringency scenarios are based on the U.S. National Research Council's *Transitions to Alternative Vehicles and Fuels* report (NRC, 2013). In both scenarios, CAFE and LCFS are extended to 2050. The medium stringency policies are based on NRC's *midrange* projections and assumptions. The medium CAFE requires "ambitious but reasonable" improvements in rolling resistance, aerodynamic drag, and mass reduction (NRC, 2013, p. 3). The medium LCFS requires large reductions in petroleum use with comparative increases in drop-in biofuels, as well as some carbon capture and storage for hydrogen production. The high stringency policies are based on NRC's *optimistic* projections and a related ZEV modelling study that uses the same model and similar assumptions (Greene et al., 2014a). The high CAFE requires "breakthrough" technological advancements that NRC estimates have a 20% chance of occurring before 2050 (2013, p. 374). The high LCFS requires gasoline to be replaced with biomass-derived synthetic gasoline, and carbon capture and storage on

[8] Because California is combined into a single region with the other ZEV States, I cannot target LCFS to only California. Therefore, simulated fuel GHG intensities are lower in the other ZEV States than in reality. This does not have significant effects on my analysis because I am focused on GHG emissions in BC.

hydrogen production to expand significantly by 2030 (Greene et al., 2014a, p. 69). Both LCFS stringencies require electricity that is 80% less GHG intensive than today.

Chapter 3.

Results

I present the results of my policy scenario simulations in the three sections below. Each section is dedicated to a research objective. Recall that the simulations for each objective build on the results of the simulations in the previous objective.

Before investigating my policy scenarios, I ran a reference case simulation to understand the potential for ZEV adoption and GHG reductions in British Columbia under the province's current policy package (the reference case). Recall that the reference case policies for British Columbia include the North American corporate average fuel economy (CAFE) standard (ends in 2025, aligned with *AEO2014's Reference Case*), a low carbon fuel standard (LCFS) (ends in 2020, aligned with *AEO2014's Reference Case*), and the BC carbon tax frozen at $30/tonne. The ZEV States in the model have a ZEV mandate in place that mimics the current ZEV mandate, which I assume stays at its 2025 stringency level until 2050.

In the reference case, ZEV adoption in British Columbia remains low. In 2050, the new vehicle market share of ZEVs reaches a median level of 4.5% (50% of values were between 2.4% and 7.4%). The probability distribution of ZEV market shares resulting from the Monte Carlo iterations is presented on the left of Figure 2 below. Well-to-wheel (WTW) GHG emissions in the passenger vehicle sector decline until approximately 2035 and then begin to increase (Figure 3). This increase occurs because CAFE ends in 2025 and LCFS ends in 2020. As a result, the GHG intensity of the active passenger vehicle stock steadily rises as vehicles that were covered by the two policies are replaced by vehicles that are not. By 2050, WTW GHG emissions decline by a median of 29% (50% of values were between 23% and 35%) from 2007 levels, far from the province's 80% target. The Monte Carlo distribution of WTW GHG reductions is presented on the left of Figure 3 below.

3.1. Objective 1: The effect of spillovers from the ZEV States' ZEV mandate on British Columbia

My first research objective is to investigate how spillovers from increasing levels of ZEV adoption in the ZEV States (California, Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont) affects ZEV adoption and WTW GHG reductions in British Columbia. I ran two simulations where the ZEV States increased their ZEV mandate stringency: first the ZEV States implement a medium stringency ZEV mandate (medium ZEV State case), then they implement a high stringency ZEV mandate (high ZEV State case). All other regions in North America (Canada and the U.S.) maintained their reference case policies.

The increased ZEV adoption in the ZEV States does not lead to large increases in ZEV adoption in British Columbia. Even under the high ZEV State case, where every vehicle sold in 2050 is a ZEV, the ZEV new vehicle market share in British Columbia reaches a median of just 11% (50% of values were between 5.8% and 19.0%). Under the medium ZEV State case, ZEV new vehicle market share in BC in 2050 reaches a median of 6.5% (50% of values were between 3.6% and 12.2%). The right two panels of Figure 2 present the Monte Carlo distributions of ZEV new vehicle market share in British Columbia in the two ZEV State ZEV mandate cases. In the high ZEV State case, the small increase in ZEV adoption translates to only a small additional improvement in GHG reductions, which reach a median of 32% by 2050 below 2007 levels (50% of values were between 26% and 38%), just 3% below the median in the reference case (Figure 3). In the medium ZEV State case, WTW GHG emissions in 2050 in the BC passenger vehicle sector decline by median of 30% (50% of values were between 24% and 36%).

Figure 2 **ZEV new vehicle market share in British Columbia in the reference case and under different ZEV States' ZEV mandate stringencies**

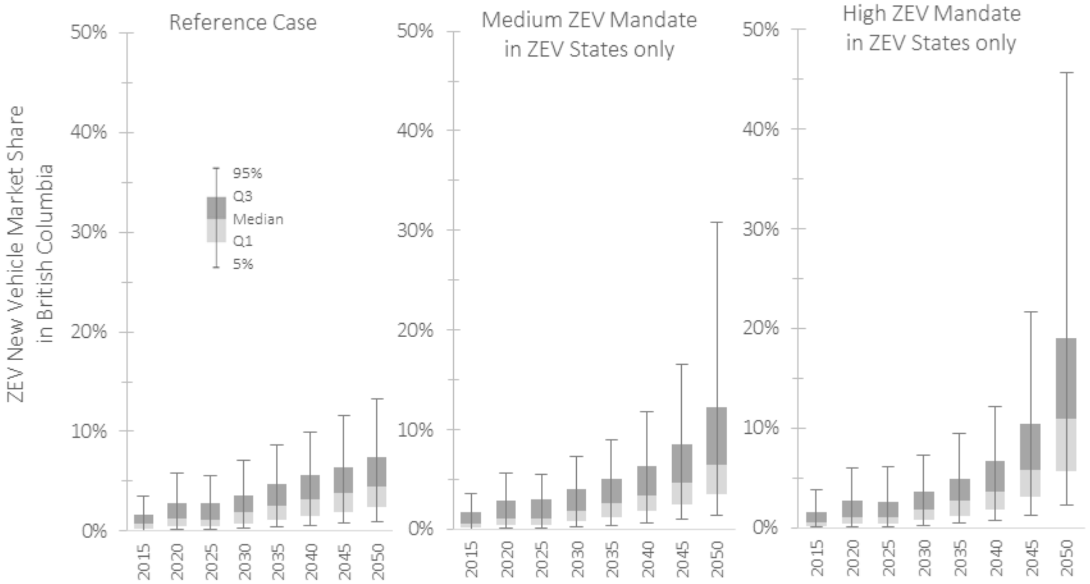
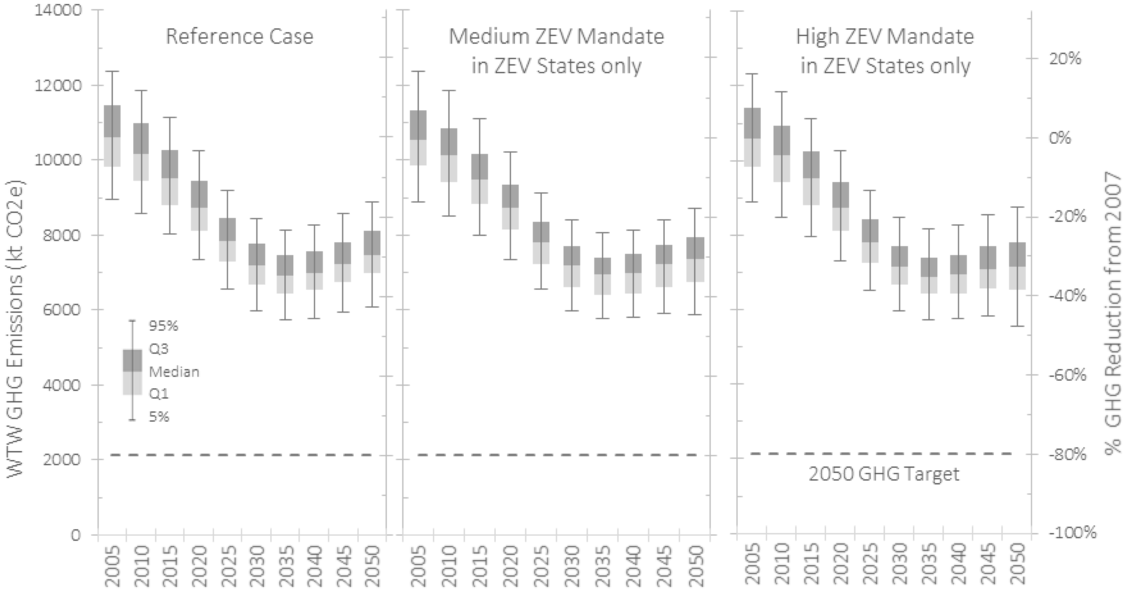


Figure 3 **WTW GHG emissions in the British Columbia passenger vehicle sector in the reference case and under different ZEV States' ZEV mandate stringencies**

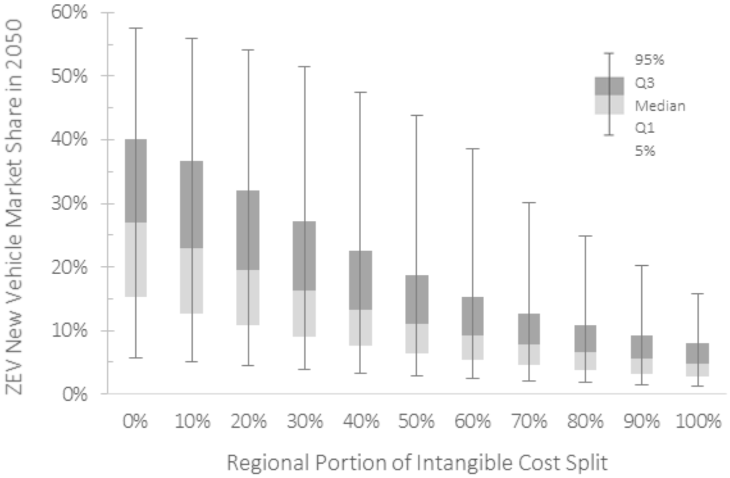


The increase in ZEV new vehicle market share is driven by decreases in capital costs and global intangible costs. Recall, capital costs decline as a vehicle technology's production increases and global intangible costs declines as its new vehicle market share across all regions increases. For example, for BEVs in the high ZEV State case, capital costs decline by 79% between 2015 and 2050. Meanwhile, BEV global intangible costs decrease by 62%. In contrast, BEV regional intangible costs in British Columbia decline by only 3%, indicating that ZEV adoption in the province is limited by persisting regional adoption barriers.

Running Monte Carlo simulations allowed me to identify under what conditions ZEV adoption may reach the higher levels at the far right of Figure 2. Using the high ZEV State case, a sensitivity analysis reveals that ZEV new vehicle market share in 2050 is most sensitive to four parameters. ZEV new vehicle market share is most sensitive to the market heterogeneity parameter, *v*: when *v* is lower, consumers are more willing to purchase more expensive vehicle technologies, and ZEV adoption increases. After market heterogeneity, ZEV adoption is most affected by the rate at which BEV capital costs decline, as expressed through the BEV progress ratio and exogenous capital cost decline rate. Finally, I find ZEV adoption is higher when the regional-global intangible cost split is more heavily weighted towards global intangible costs (i.e. intangible costs are more affected by global developments than regional developments). In this situation, intangible costs in British Columbia are more dependent on ZEV new vehicle market share in the ZEV States, so the province benefits from greater spillovers that drive down intangible costs. Given the novelty of this parameter and the uncertainty in its value, I conducted additional sensitivity analysis to better understand how my assumptions about it may affect my results.

I ran a series of 11 Monte Carlo simulations covering the full range of possible intangible cost split values. Each simulation involved 1000 iterations that use the same set of random variables for all uncertain input parameters, except the intangible cost split. The intangible cost split varied by 10% in each simulation, starting at 0% regional (100% global) and ending at 100% regional (0% global). As can be seen in Figure 4, the resulting 2050 ZEV new vehicle market shares vary considerably depending on the assumed intangible cost split. The more globally weighted the intangible cost split, the less ZEV adoption is held back by regional intangible costs (representing regional adoption barriers), and the more British Columbia benefits from spillovers from adoption in other regions. However, even with the highest ZEV new vehicle market share (far left in Figure 4), British Columbia still does not achieve its 2050 GHG target (80% emissions reductions) in the passenger vehicle sector. This result is consistent with the objective 2 results discussed in the next section, where I find that higher ZEV new vehicle market shares are required to hit the target.

Figure 4 **Sensitivity of British Columbia's 2050 ZEV new vehicle market share to the regional-global intangible cost split parameter**



3.2. Objective 2: The need for strong ZEV policy to achieve British Columbia 2050 GHG target

Building on the results above, I next ran simulations to investigate whether British Columbia can achieve its GHG target by implementing stronger transportation-focused policies that do not specifically target ZEVs, or if the province needs to focus on increasing ZEV adoption as well. I simulated two policy packages centered around medium and high stringency CAFE and LCFS policies (medium BC package case and high BC package case). In both cases, the ZEV States maintain their high stringency ZEV mandate, thereby maximizing the potential for spillovers to help increase ZEV adoption in British Columbia. I analyze the likelihood of British Columbia achieving its GHG target in the passenger vehicle sector. Where necessary, I then run simulations to determine what level of ZEV adoption is needed for each policy package to achieve the GHG target in 80% of Monte Carlo iterations.

Figure 5 summarizes the WTW GHG emissions trajectories in the BC passenger vehicle sector under both policy packages. The medium BC package case (left) is not strong enough to hit the 80% GHG reductions in the passenger vehicle section in any of the iterations. It reaches a median GHG reduction of 61% (50% of values were between 57% and 64%). The high BC package case reaches a median 78% GHG reduction (50% of values were between 76% and 80%), with 24.3% of the Monte Carlo iterations hitting the 2050 target in the passenger vehicle sector (far right). Figure 6 presents a magnified view of 2050 GHG emissions in the BC passenger vehicle sector. The bars left of the dashed line represent the iterations that achieve the GHG target. One can interpret this as British Columbia has approximately a 24% chance of achieving its GHG target with the high stringency CAFE and LCFS policy package (but no ZEV mandate) under this set of conditions.

Figure 5 **WTW GHG emissions reductions in the British Columbia passenger vehicle sector under CAFE and LCFS policy packages with a carbon tax but without a ZEV mandate**

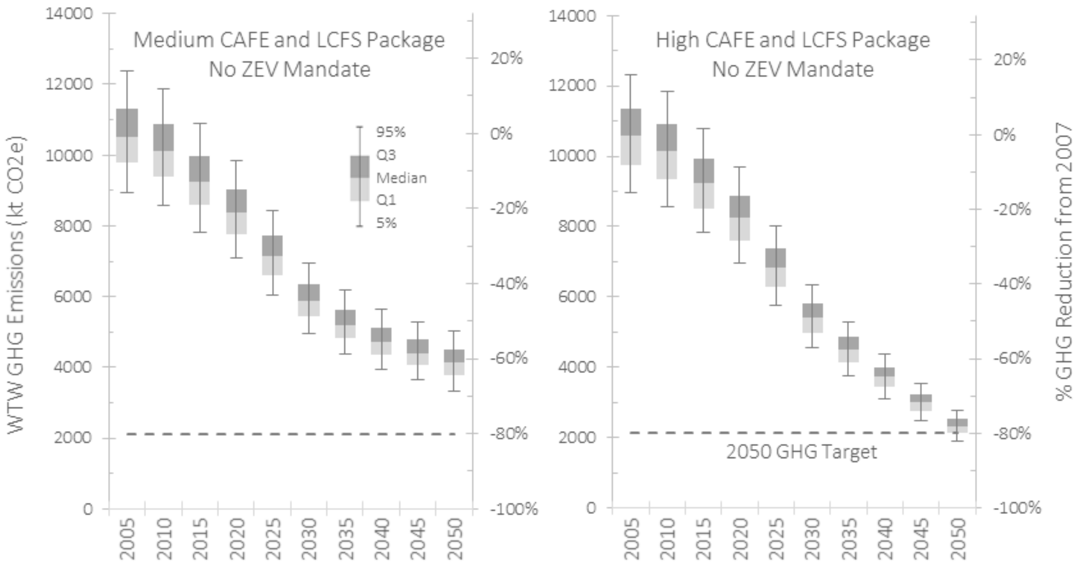
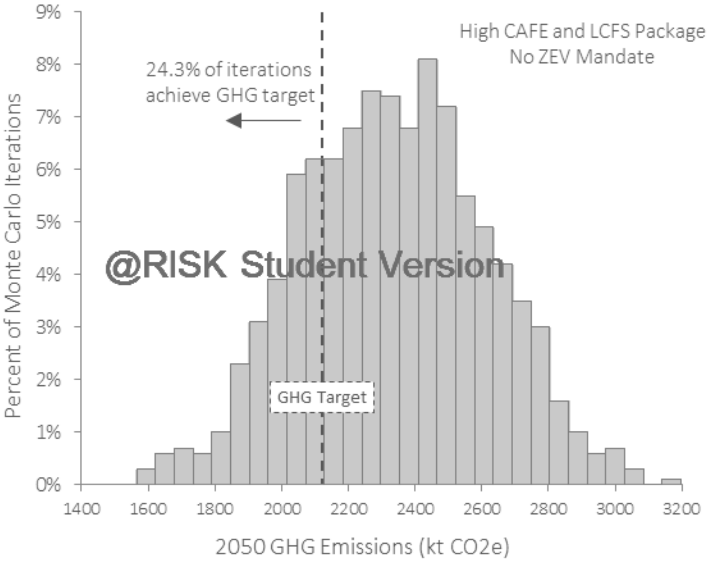


Figure 6 **Frequency distribution of Monte Carlo iterations that hit the 2050 GHG target when British Columbia implements the high stringency CAFE and LCFS policy package with a carbon tax but without a ZEV mandate**

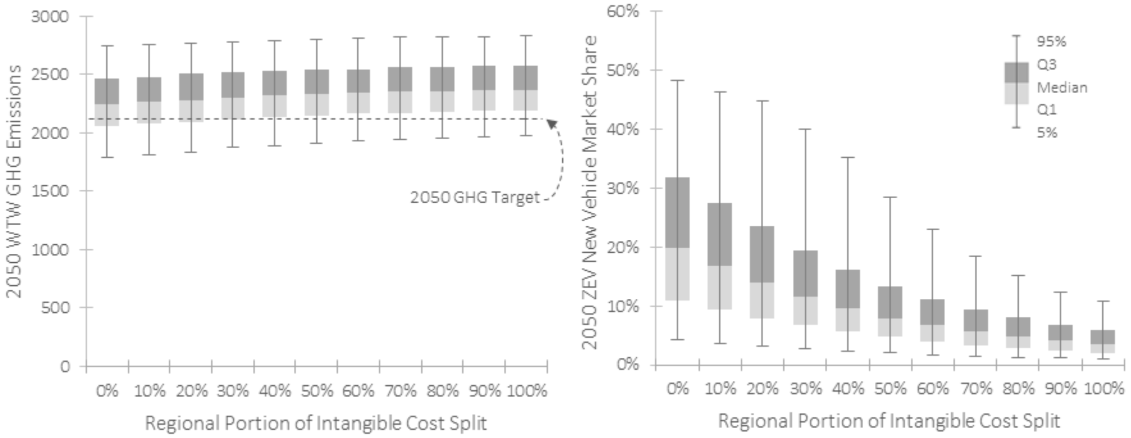


I conducted a sensitivity analysis to better understand the conditions under which the high stringency CAFE and LCFS policy package achieves 80% GHG reductions in the passenger vehicle sector. Only three significant parameters emerged. Projected VKT demand has by far the largest influence, where lower VKT demand leads to fewer GHG emissions. As noted at the top of section 2.2, I account for uncertainty in future VKT demand by assigning Monte Carlo distributions to VKT's annual growth rate and by allowing VKT demand to fluctuate between regions based on historical demand (e.g. Canada demands 6% to 8% of the total U.S. demand). These fluctuations between regions effectively mimic a situation where British Columbia manages to either decrease citizen's demand for travel, or shifts travel demand from passenger vehicles to other means of transportation (e.g. cycling and public transit). The other two key parameters driving GHG reductions are the market heterogeneity parameter and the BEV progress ratio, both of which were discussed in section 3.1.

The regional-global intangible cost split did not emerge as a very influential factor in determining 2050 GHG emission reductions for these particular scenarios, but warrants further investigation given the novelty of the parameter and uncertainty in its value. As such, I again conducted the sensitivity analysis described in the last paragraph of section

3.1. I conducted this analysis using the high BC package case. The resulting 2050 GHG emissions (left) and associated ZEV new vehicle market shares (right) for the BC passenger vehicle sector are presented in Figure 7. When the intangible cost split is weighted more globally, ZEV adoption increases and British Columbia achieves its GHG target in the passenger vehicle sector in a higher number of iterations. If intangible costs are 100% global (far left), 32.7% of iterations reach the 2050 GHG target, whereas only 16.7% achieve the target at the opposite extreme. I ran the same sensitivity analysis on the medium BC package case and found that no iterations hit the GHG target.

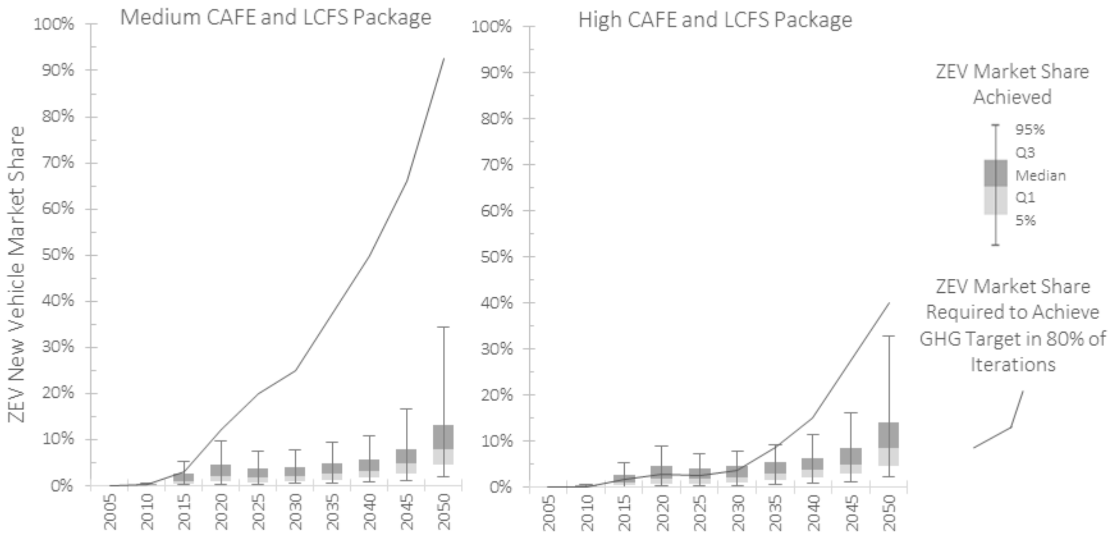
Figure 7 **Sensitivity of British Columbia's 2050 WTW GHG emissions (left) and ZEV new vehicle market share (right) to the intangible cost split parameter in the high stringency CAFE and LCFS policy package with a carbon tax but without a ZEV mandate**



The results above indicate that British Columbia is unlikely to achieve its 2050 GHG target in the passenger vehicle sector without higher levels of ZEV adoption, and in particular without strong ZEV policy (like a ZEV mandate) to achieve the required levels of ZEV adoption. Even under the most optimistic assumptions regarding intangible cost spillovers, I find the high stringency CAFE and LCFS policy package only achieves the GHG target in approximately 33% of iterations. Recall that achieving these particular high stringency CAFE and LCFS policies requires technology breakthroughs that the NRC (2013, p. 115) authors estimate only have a 20% chance of occurring before 2050. The more realistic medium stringency CAFE and LCFS package does not hit the GHG target in any iterations. Therefore, to better understand the potential need for ZEVs, I determined the ZEV adoption required for each policy package to achieve the GHG target in 80% of Monte Carlo iterations.

Figure 8 presents the ZEV new vehicle market share achieved under each policy package (box plots) and the ZEV new vehicle market share required for British Columbia to have an 80% chance of hitting its GHG target (line). Recall the ZEV States implement a high stringency ZEV mandate in both cases (i.e. ZEVs have 25% new vehicle market share in 2030, 60% in 2040, and 100% in 2050). I find that the required ZEV new vehicle market share varies considerably between the two policy packages, and thus on the progression of vehicle and fuel technology development. Under the high BC package case's more optimistic assumptions, ZEV new vehicle market share must reach 15% by 2040 (vs. median 3.7% achieved) and 40% by 2050 (vs. 8.5%). In the medium BC package case, ZEV new vehicle market share must reach 50% by 2040 (vs. 3.1%) and 92.5% by 2050 (vs. 7.9%). The 2040 minimum new vehicle market shares are critical due to the rate of turnover in the passenger vehicle stock. In all cases, approximately one third of ZEVs sold in 2050 are PHEVs and two thirds are BEVs. Only a negligible number of HFCVs are sold.

Figure 8 **ZEV new vehicle market share in British Columbia under different policy packages without a ZEV mandate and additional ZEV market share required to achieve the 2050 GHG target in 80% of iterations**

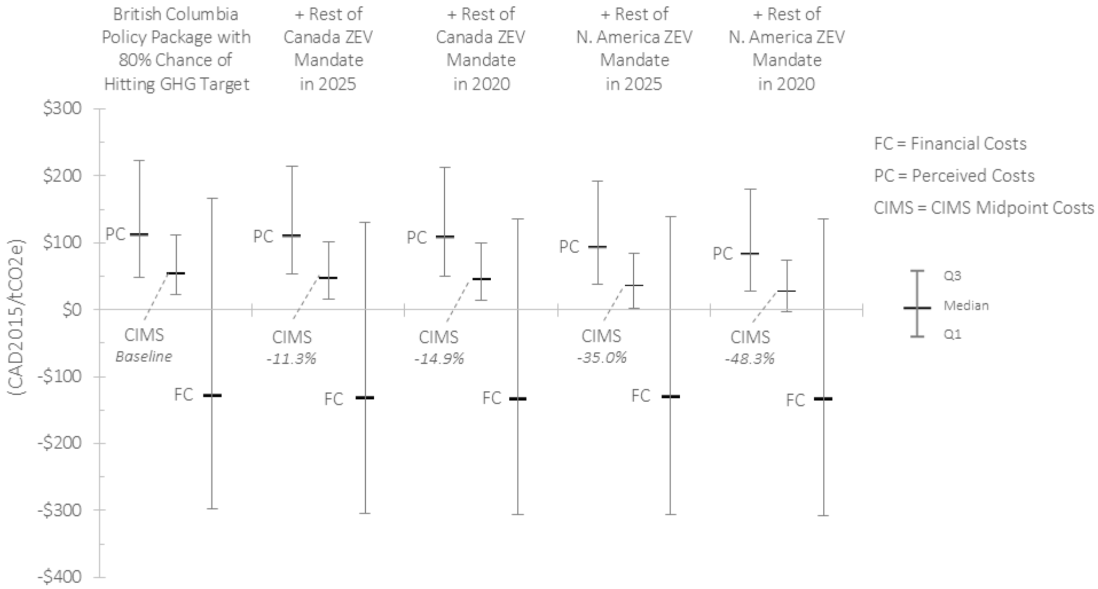


3.3. Objective 3: Reductions in British Columbia's abatement costs as other regions increase ZEV adoption

My final objective focuses on how increased ZEV adoption outside British Columbia affects GHG abatement costs in British Columbia. I run a series of simulations where regions adopt medium stringency ZEV mandates starting in different periods: the rest of Canada in 2020, the rest of Canada in 2025, the rest of North America in 2020, and the rest of North America in 2025. In each case, British Columbia implements the medium CAFE and LCFS policy package discussed in section 3.2 with a ZEV mandate at the stringency necessary for the province to have an 80% chance of achieving its 2050 GHG target in the passenger vehicle sector (line on left side of Figure 8, with 25% ZEV new vehicle market share in 2030, 50% in 2040 and 92.5% in 2050). In all these scenarios, the ZEV States maintain a high stringency ZEV mandate (which, for reference, is 25% in 2030, 60% in 2040, and 100% in 2050).

Figure 9 summarizes the results for each simulation, presenting the financial, perceived, and CIMS midpoint cost measures described in section 2.8. Recall that financial costs account for consumer spending on lifecycle capital, energy, and maintenance costs, while perceived costs include all these and intangible costs. CIMS midpoint costs find a midpoint between these values. As a reference point, the far left of the figure presents the cost-effectiveness values when British Columbia implements its policy package, but before other regions adopt their ZEV mandates. In this case, the CIMS midpoint cost estimate is median \$56/tCO$_2$e reduced (50% of values were between -\$9/tCO$_2$e and \$164/tCO$_2$e). The perceived cost value is approximately \$114/tCO$_2$e (50% of values were between \$80/tCO$_2$e and \$170/tCO$_2$e) and the financial cost is approximately -\$130/tCO$_2$e (50% of values were between -\$297/tCO$_2$e and \$166/tCO$_2$e). The negative financial cost value indicates that the policy package yields a net benefit for British Columbia consumers by 2050. A net benefit is possible if the total discounted financial cost consumers spend on passenger vehicles over the time period decreases compared to the reference case. In this case, financial costs are negative due to both lower fuel costs and a decrease in the demand for new vehicles resulting from an increase in the average capital cost of vehicles. This financial cost value does not account for potential increases in spending on other forms of transportation, such as public transit.

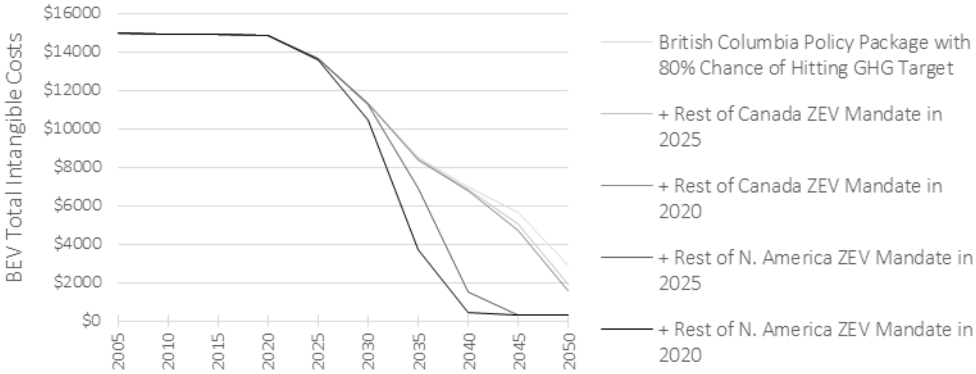
Figure 9 Abatement cost-effectiveness of a ZEV policy package when only British Columbia and the ZEV States implement a ZEV mandate versus when other regions adopt ZEV mandates



The remaining (right) four scenarios in Figure 9 present the cost-effectiveness of GHG reductions as the other regions adopt ZEV mandates. The text below the x-axis summarizes the percentage improvement (reduction) in the CIMS midpoint cost measure relative to the scenario described in the previous paragraph. The results indicate that considerable savings are generated as other regions increase ZEV adoption. When the rest of Canada adopts a medium stringency ZEV mandate, CIMS midpoint abatement costs are 11% to 15% lower, depending on when the mandate is implemented. If the rest of North America adopts a medium stringency ZEV mandate, CIMS midpoint abatement costs are reduced by 35% to 48%, with greater cost savings when regions increase ZEV adoption sooner. In all cases, British Columbia's GHG reductions remain steady so improvements in cost-effectiveness are due to lower overall abatement costs between now and 2050.

The lower CIMS midpoint abatement costs are primarily the result of lower perceived costs, which are driven by more rapidly declining global intangible costs for BEVs and PHEVs. Figure 10 presents the BEV intangible cost trajectory in each scenario. More stringent policy scenarios are represented by progressively darker lines. When the rest of North America joins British Columbia and the ZEV States in facilitating a transition to ZEVs, BEV intangible costs reach their predetermined minimum 10 to 15 years faster than if British Columbia and the ZEV States act alone. The difference between each scenario is due entirely to global intangible cost reductions. Regional intangible costs do not change.

Figure 10 **BEV intangible cost trajectories in British Columbia under different regional ZEV mandate scenarios**



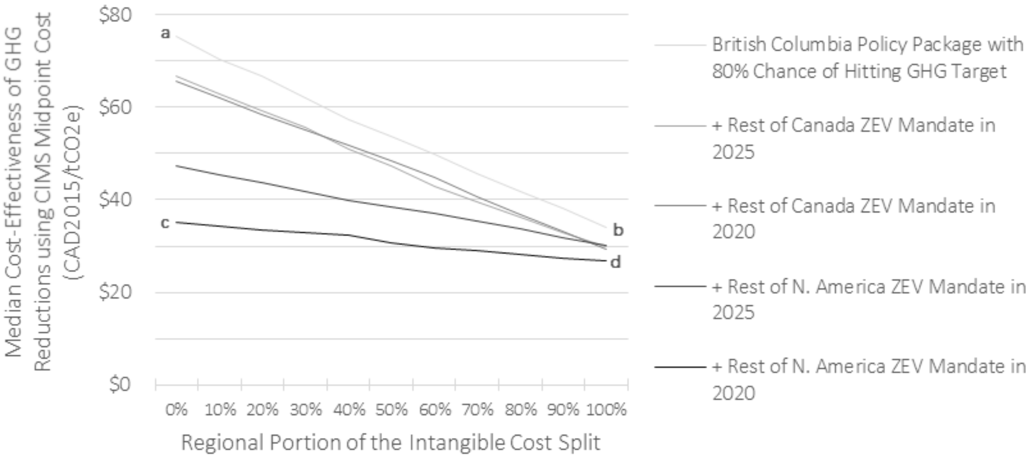
Note: All intangible cost declines are due to lower global intangible costs.

As with my previous objectives, I conducted a sensitivity analysis to understand how the regional-global intangible cost split affects my results. Figure 11 presents the range of CIMS midpoint abatement cost estimates for each assumed intangible cost split. If the split is more regionally weighted (right), intangible costs in British Columbia depend less on vehicle adoption in other regions and CIMS midpoint abatement costs in the five scenarios converge. In this case, CIMS midpoint abatement costs are 21% lower (point b to d) when the rest of North America implements a ZEV mandate in 2020. The cost decline is due entirely to lower capital costs. If the split is more globally weighted (left), intangible costs in British Columbia are almost entirely dependent on vehicle adoption in other regions. In this case, CIMS midpoint abatement costs decline by 53% (point a to c) when the rest of North America adopts a ZEV mandate in 2020.

Additionally, I find that the intangible cost split assumption has a large effect on British Columbia's abatement costs in the case where the other regions do not adopt ZEV mandates. Recall that the CIMS midpoint cost estimate has a median value of $\$56/tCO_2e$ on the left of Figure 9. Relative to this value, GHG reductions are 35% less cost-effective when intangible costs are 100% global (point a) and 40% more cost-effective when 100%

regional (point b). Altogether, these results indicate that assumptions about the intangible cost split have a significant impact on abatement costs.

Figure 11 **Sensitivity of abatement cost-effectiveness to the regional-global intangible cost split**



Chapter 4.

Discussion

The purpose of this study is to investigate whether a region needs its own stringent ZEV-specific policy to achieve a long-term GHG target in the passenger vehicle sector, or whether it can free-ride off stronger ZEV policy in another region. I used a vehicle choice model of the North American passenger vehicle sector to simulate a case study of British Columbia (a small North American region) attempting to free-ride off a ZEV mandate in California and the other ZEV States (a much larger North American region). A novel and important feature of my model is a parameter that accounts for the way regional and global developments uniquely influence ZEV adoption barriers inside a region. I term this the regional-global intangible cost split parameter. In the sections below, I discuss my findings related to each of my three research objectives, consider policy implications, and reflect on my intangible cost split parameter.

As noted in other long-term ZEV modelling studies (e.g. Greene et al., 2014a, 2014b; NRC, 2013), the results of this study are subject to a high degree of uncertainty. Future technology developments and related market responses are unknowable and will shape vehicle adoption, GHG reductions, and the costs governments may need to incur to meet GHG targets. Furthermore, our current capacity to quantify the non-financial adoption barriers that I include in intangible costs is still limited (as discussed in section 2.5). To better understand the influence of this uncertainty, I presented my results in the context of Monte Carlo simulations and sensitivity analyses. Discussed in this context, my findings may provide valuable insights for future modellers and policymakers working to reduce GHG emissions. I conclude with a brief discussion of limitations and opportunities for future research (section 4.6).

4.1. Objective 1: Regions likely cannot effectively free-ride off other regions’ ZEV policy

This case study modelling exercise indicates that small North American regions (like British Columbia) likely cannot achieve long-term GHG targets by free-riding off stronger ZEV policy in other regions. Even when the ZEV States force ZEVs to comprise 100% of new vehicle sales in their regions in 2050, the resulting spillovers in decreased capital and global intangible costs that British Columbia experiences are not enough to reach the ZEV adoption required to hit the province’s GHG target in the passenger vehicle sector (80% reduction relative to 2007). Rather, ZEV new vehicle market share is limited by relatively steady regional intangible costs, i.e. regional adoption barriers. This finding persists even when maximizing intangible cost spillovers (by assuming the intangible cost split parameter is 100% global) and when British Columbia increases its carbon tax and implements strong, but achievable corporate average fuel economy (CAFE) and low carbon fuel standard (LCFS) policies. Although this study focuses on a ZEV mandate, regional spillovers result from increases in ZEV adoption, so this finding applies to any policy that increases ZEV adoption. This study is a novel investigation of free-riding and regional ZEV spillovers, so there is limited existing research to compare it to. As part of a larger modelling study, Greene et al. (2014b) investigate a scenario where California freezes their ZEV mandate while international ZEV sales increase. The authors find that the spillovers from international sales are not enough for California ZEV adoption to reach the level necessary to achieve the state’s 2050 GHG target in the passenger vehicle sector. Similar to the present study, they found that new vehicle market share was limited by a lack of regional electric vehicle refuelling infrastructure and the limited diversity of electric vehicle models in the state, despite decreases in capital costs.

4.2. Objective 2: Strong regional ZEV policy may be crucial to achieving long-term GHG targets

Within the limits of the scope and assumptions of this case study assumptions, my findings strongly suggest that ZEVs likely play a critical role in achieving long-term GHG targets in the passenger vehicle sector, at least in the U.S. and Canadian regions simulated. Without working to increase ZEV adoption, I find that the optimistic CAFE and LCFS with carbon tax policy package I simulated achieves British Columbia’s 2050 GHG target in the passenger vehicle sector only 25% of the time. These two optimistic policies depend on technological breakthroughs that may have only a 20% chance of occurring by 2050 (NRC, 2013). A policy package centered around the more realistic CAFE and LCFS policies I modelled (also based on NRC, 2013) with a moderate carbon tax, does not hit the target in any iterations. As such, it seems highly likely that ZEVs will play a crucial role in achieving long-term GHG targets. This is consistent with Williams et al. (2012), who found that vehicle electrification is likely pivotal to achieving deep GHG reductions in California by 2050.

The ZEV adoption levels I find necessary to achieve British Columbia's 2050 GHG target are also similar to those found in other studies. Under the more realistic (medium stringency) CAFE and LCFS policy package, I find ZEVs must make up half of new vehicles sold in 2040 and over 90% in 2050 (see Figure 8). The 2040 market share requirement is critical in my simulations due to the time it takes for passenger vehicles to be replaced. For comparison, the California Air Resources Board (2009) estimates all new passenger vehicles sold in 2040 must be ZEVs, even with more fuel efficient vehicles, less GHG intensive fuels, significantly higher biofuel availability, and lower vehicle travel demand. Other modelling studies of California and the other ZEV States find that most or all new vehicles sold in 2050 must be ZEVs, with new vehicle market shares in 2050 needing to reach 75% (Greene et al., 2014a, 2014b), 94% (Wei et al., 2013), or 100% (Yang et al., 2015). Similarly, Greenblatt (2015) simulated all current and proposed California passenger vehicle policies and found they are not enough to achieve the state's 2050 GHG target, even though ZEVs comprise 60% of the total passenger vehicle fleet by 2050.

4.3. Objective 3: Regional GHG abatement costs can be decreased through interregional collaboration

Further exploring the effects of regional spillovers, I find that British Columbia's GHG abatement costs (using the CIMS midpoint estimate) in the passenger vehicle sector between now and 2050 may decrease considerably as other regions increase ZEV adoption. Abatement cost reductions in the province are particularly high (35% to 50%) when all of North America adopts a ZEV mandate. The savings occur even these other regions wait a decade after British Columbia has implemented its ZEV mandate to implement their own ZEV mandate. The abatement cost reductions are driven by steeper declines in global intangible costs, i.e. more quickly overcoming global adoption barriers that are otherwise limiting ZEV adoption in the province. As such, the abatement cost savings resulting from intangible cost spillovers are higher when regional ZEV adoption is limited more by global adoption barriers than regional adoption barriers, i.e. the regional-global intangible cost split is more globally weighted (see Figure 11).

The present study may be the first investigation of what happens with a region's abatement costs when other jurisdictions increase ZEV adoption *after* the region has implemented its own ZEV policy. Greene et al. (2014b) looked at the reverse. They found that when the ZEV States implement a ZEV mandate *before* the rest of the U.S., the rest of the U.S. experiences a higher net benefit from transitioning to ZEVs because of spillover benefits from the ZEV States. Whereas their results may be used to show the benefit of delaying ZEV policy until other regions enact their own strong ZEV policy, my results indicate that regions can also decrease their overall abatement costs by taking a leadership role if they are successful in convincing other regions to eventually join them in facilitating a transition to ZEVs.

4.4. Policy implications

Altogether, the results of this study indicate that regions within North America (Canada and the U.S.) likely must implement their own strong ZEV policy to achieve their long-term GHG reduction targets in the passenger vehicle sector. The policies I simulated to induce large increases in vehicle fuel efficiency (e.g. CAFE), large decreases in fuel GHG intensity (e.g. LCFS), and raise the price of activities that result in GHG emissions (e.g. carbon tax) appear to be necessary, but insufficient on their own. (It may be possible to achieve the 2050 GHG target in the passenger vehicle sector with evener stronger CAFE, LCFS, and carbon tax policies than those simulated here, but would require further research.) Furthermore, the level of ZEV adoption necessary to supplement these policies appears unlikely to occur through regional spillover benefits alone. Because my modeling exercise focused only on Canada and North America, it is not clear how applicable these results are to other developed countries (e.g. in the EU) or developing countries. However, given that the model structure I use has been and can be applied to other regions, I suspect that my finding regarding the need for strong regional ZEV policy to hit long-term GHG targets would be applicable to other regions as well.

My results suggest that regional ZEV policies may be more effective if targeting both regional and global adoption barriers. Regional intangible costs limit ZEV adoption in some of my simulations, whereas global intangible costs limit ZEV adoption in others. Regions may thus want to follow California's approach of implementing a combination of demand-focused and supply-focused policies. Demand-focused policies aim to stimulate consumers to buy ZEVs by lowering adoption barriers directly, such as vehicle purchase discounts and the installation of electric vehicle charging infrastructure, and typically affect only regional sales. Supply-focused policies stimulate automakers to increase the availability of ZEVs and help develop the ZEV market, and can affect both regional and global sales. As such, supply-focused policies encourage automakers to lower adoption barriers that may be difficult for regional governments to influence directly, such as increasing marketing efforts at dealerships or offering a wider diversity of ZEV models. Other studies have found that the limited diversity of ZEV models may be a particularly important factor limiting higher adoption rates (Axsen et al., 2015; Greene et al., 2014b; Lutsey, 2015; Struben and Sterman, 2008).

Considering the potential need for supply-focused policy, the ZEV mandate may be a particularly useful policy for North American regions. California's ZEV mandate specifically targets vehicle suppliers and thus at least some of the adoption barriers that I categorize as partially or entirely global. Likely as a result, California sells a higher diversity of ZEV models than other regions (Lutsey, 2015). The mandate has already been adopted by nine other U.S. states and may thus offer an excellent opportunity for increased interregional collaboration focused on implementing strong ZEV policy. Aside from the ZEV mandate, the most oft-cited strong ZEV policies exist in Norway. Norway has a portfolio of demand-focused policies that centre around exempting consumers from extremely high vehicle taxes (Hannisdahl et al., 2013; The Nordic Page, 2015). These vehicle taxes do not exist in North American regions, and a survey of citizens in British Columbia indicates that strong ZEV regulations may be more acceptable than tax-based policies (Rhodes et al., 2014).

Finally, my findings suggest that small North American regions (like British Columbia) may want to collaborate with other regions to reduce the costs they must incur to facilitate a transition to ZEVs. Increasing ZEV adoption outside a region drives down capital costs and lowers global adoption barriers, thus lowering the financial and non-financial barriers limiting ZEV adoption in the region. As such, governments playing a leadership role in facilitating a transition to ZEVs have an incentive to lobby other jurisdictions to enact strong policy. Existing memoranda of understanding, like the *Pacific Coast Action Plan on Climate and Energy* (Government of California et al., 2013), and other similar agreements, like the International Zero-Emission Vehicle Alliance (BC MOE, 2015), typically do not require specific policy action. However, these existing collaborations may offer useful platforms on which to lobby for strong policy action in lagging regions, and to gain immediate commitment to strong and specific policies in member jurisdictions.

4.5. Reflections on the regional-global intangible cost method

The regional-global intangible cost split parameter is a key feature of this modelling exercise. I use the parameter to capture the effect that both regional and global developments have on ZEV adoption barriers and the way they influence regional purchase decisions (Lutsey et al., 2015). Regional intangible costs decline based on a technology's regional new vehicle market share and global intangible costs decline based on its new vehicle market share across all regions. I based the value of the intangible cost split parameter on other modelling and survey studies that quantify the influence that non-financial factors have on vehicle purchase decisions. Given the novelty of this approach and the differences in the way other studies treat and quantify these factors, I assign the parameter a large Monte Carlo uncertainty distribution and conduct sensitivity analyses to better understand how my assumptions affect my results. This differs from previous ZEV policy modelling studies that tend to use either a single intangible cost parameter (e.g. Fox, 2013) or use multiple parameters to represent a limited set of non-financial factors that affect ZEV adoption (e.g. Greene et al., 2014a, 2014b; Walther et al., 2010). The parameters in the latter set of studies may or may not account for regional versus non-regional influences.

I find that assumptions about the split parameter have a significant effect on two important model outcomes. First, it affects the ZEV new vehicle market share that British

Columbia can achieve through free-riding. If I assume intangible costs are 100% global, rather than my baseline assumption of 50/50, I find that British Columbia's ZEV new vehicle market share more than doubles (see Figure 4). Second, the parameter affects abatement costs when British Columbia implements a policy package that achieves the province's 2050 GHG target in the passenger vehicle sector in 80% of Monte Carlo iterations. Compared to my baseline intangible cost split assumption, the policy package is 40% less cost-effective if intangible costs are 100% global, and 35% more cost-effective if they are 100% regional (see Figure 11).

Based on my experience, I suggest that future ZEV modelling studies may be improved by representing both the regional and non-regional developments that can affect adoption barriers. As noted by several of the articles reviewed for this study (e.g. Axsen et al., 2015; Bočkarjova et al., 2014; Greene et al., 2014a, 2014b), these factors are already subject to a high degree of uncertainty. Therefore, modelling studies may also be improved by explicitly accounting for uncertainty in these parameters and communicating how such uncertainty affects key study outcomes.

4.6. Limitations and future research

The results of this study are especially dependent on assumptions made about the technological development of vehicles and fuels between now and 2050. Although my fuel efficiency and GHG intensity values are based on a detailed technological assessment by the National Research Council (2013), the actual trajectory of technological development is unknowable and could take several different paths. Alternative developments that I did not simulate include advanced biofuel vehicles meeting ZEV mandate requirements, HFCV costs declining enough to significantly increase adoption, BEVs satisfying less VKT demand than other vehicle technologies, PHEV driving patterns leading to more or less GHG emissions, and the potential effects of car sharing and autonomous vehicles. Each of these could increase or decrease the ZEV adoption necessary to achieve long-term GHG targets as well as a region's GHG abatement costs.

Future research could also investigate the effect of different global ZEV adoption scenarios to better understand how they influence declining capital costs and thus ZEV adoption and GHG reductions in the region being studied (in this case, British Columbia). My approach assumes that global ZEV adoption follows the same trajectory as adoption in North America. Future studies could separate the global region into multiple sub-regions (e.g. China, the European Union) and simulate different adoption scenarios for each.

A key limitation of my model is my lack of endogenous representation of the fuel supply sector. I use exogenous schedules to define the price and GHG intensity trajectories of all fuels until 2050. As such, the prices of fuels in my model do not change in response to changes in their demand. Therefore, my simulations do not account for how a massive shift from gasoline-powered vehicles to electric vehicles may affect gasoline prices. If my model did account for this effect, gasoline prices may decline significantly, thus increasing consumer preference for gasoline vehicles. It is unclear exactly how this would affect the GHG impact of ZEV policies, but it would likely make it more difficult for policymakers to increase consumer demand for ZEVs. How difficult will depend significantly on improvements in the cost of ZEVs and how the price of electricity is affected by a shift to low-carbon and renewable sources.

My technology-neutral ZEV mandate design may affect two of my main findings. I allow any combination of ZEVs (BEVs, PHEVs, and HFCVs) to meet the mandate’s minimum new vehicle market share requirements. California’s ZEV mandate is designed to force an increasing percentage of BEVs and HFCVs, while decreasing the new vehicle market share requirements that can be met by PHEVs. Following California’s more technology-specific mandate design may decrease the total ZEV new vehicle market share required to achieve long-term GHG targets because the ZEVs that are being sold would likely be lower emission (depending on e.g. driving habits). Forcing fewer technologies may also lead to faster capital and intangible cost declines for the forced technologies. This may increase the opportunity for a region to free-ride off spillovers from another region, although I suspect regions would still require their own ZEV policy given the low potential for free-riding found in this study. Additionally, future research could investigate how a carbon tax could be used to stimulate the level of ZEV adoption I find necessary to achieve British Columbia’s 2050 GHG target in the passenger vehicle sector. All policies could be kept frozen with the exception of the carbon tax, which could be steadily raised until the required ZEV new vehicle market shares are reached. This may provide insight into how high carbon taxes would need to be to force a transition to ZEVs, as well as perhaps implying how politically acceptable (or unlikely) such a policy may be.

My findings and the limitations in my methods suggest that three streams of research may support future modelling studies and policymaker decisions. First, researchers should continue to refine the representation of non-financial adoption barriers in modelling studies, including differentiating between the way regional and non-regional developments lower adoption barriers. Second, given the consistency in study findings regarding the role of ZEVs, researchers should continue to investigate precisely what barriers are limiting a region's ZEV adoption and what policies are successfully overcoming them. Both types of studies have increased in recent years (e.g. Axsen et al., 2015; Lutsey et al., 2015; Vergis and Chen, 2014; Vergis et al., 2014) and offer useful insights for policymakers. Third, given the high degree of uncertainty regarding future technological development, future modeling studies could investigate how ZEV policy strategies may need to be adapted under different technology trajectory assumptions, and how this may affect abatement costs.

References

Alvarez-Daziano, R., Bolduc, D., 2009. Canadian consumers perceptual and attitudinal responses toward green automobile technologies: an application of hybrid choice models, 2009 EAERE-FEEM-VIU European Summer School in Resources and Environmental Economics: Economics, Transport and Environment. Working paper accessed at http://www. feem-web. it/ess/files/alvarezdaziano. pdf on December 14.

Axsen, J., Goldberg, S., Bailey, J., Kamiya, G., Langman, B., Cairns, J., Wolinetz, M., Miele, A., 2015. Electrifying Vehicles: Insights from the Canadian Plug-in Electric Vehicle Study. Vancouver, Canada.

Axsen, J., Mountain, D.C., Jaccard, M., 2009. Combining stated and revealed choice research to simulate the neighbor effect: The case of hybrid-electric vehicles. Resour. Energy Econ. 31, 221–238. doi:10.1016/j.reseneeco.2009.02.001

Azar, C., Sandén, B. a., 2011. The elusive quest for technology-neutral policies. Environ. Innov. Soc. Transitions 1, 135–139. doi:10.1016/j.eist.2011.03.003

Bakker, S., Farla, J., 2014. Electrification of the car – Will the momentum last? Environ. Innov. Soc. Transitions. doi:10.1016/j.eist.2014.07.002

Bandivadekar, A., Bodek, K., Cheah, L., Evans, C., Groode, T., Heywood, J., Kasseris, E., Kromer, M., Weiss, M., 2008. Fueling our Transportation Future: On the Road in 2035: Reducing Transportation’s Petroleum Consumption and GHG Emissions. Cambridge, Massachusetts.

Bastani, P., Heywood, J.B., Hope, C., 2012. The effect of uncertainty on US transport-related GHG emissions and fuel consumption out to 2050. Transp. Res. Part A Policy Pract. 46, 517–548.

Bataille, C., Jaccard, M., Nyboer, J., Rivers, N., 2006. Towards General Equilibrium in a Technology-Rich Model with Empirically Estimated Behavioral Parameters. Energy J. 27, 93–112. doi:10.2307/23297047

BC MEM, 2013. Determination of Carbon Intensity for the Renewable and Low Carbon Fuel Requirements Regulation (Information Bulletin RLCF-006).

BC MOE, 2015. B.C. joins international alliance for zero-emission vehicles [WWW Document]. Br. Columbia Gov. News. URL https://news.gov.bc.ca/releases/2015ENV0081-002066 (accessed 1.20.16).

BC MOE, 2008. Legislation Introduced to Cut Vehicle Emissions.

BC MOF, 2015. Tax Rates on Fuels: Motor Fuel Tax Act and Carbon Tax Act. Victoria, BC.

Bhat, C.R., Sen, S., Eluru, N., 2009. The impact of demographics, built environment attributes, vehicle characteristics, and gasoline prices on household vehicle holdings and use. Transp. Res. Part B Methodol. 43, 1–18. doi:10.1016/j.trb.2008.06.009

Bočkarjova, M., Rietveld, P., Knockaert, J., Steg, L., 2014. Dynamic consumer heterogeneity in electric vehicle adoption. innovation 3, 4.

Bolduc, D., Boucher, N., Alvarez-Daziano, R., Pavillon, J.A., DeSeve, Q.C., 2008. Hybrid Choice Modeling of New Technologies for Car Use in Canada: A Simulated Maximum Likelihood Approach.

Brown, M.B., 2001. The Civic Shaping of Technology: California's Electric Vehicle Program. Sci. Technol. Hum. Values 26, 56–81.

Brownstone, D., Bunch, D.S., Train, K., 2000. Joint mixed logit models of stated and revealed preferences for alternative-fuel vehicles. Transp. Res. Part B Methodol. 34, 315–338. doi:http://dx.doi.org/10.1016/S0191-2615(99)00031-4

Brownstone, D., Train, K., 1998. Forecasting new product penetration with flexible substitution patterns. J. Econom. 89, 109–129. doi:http://dx.doi.org/10.1016/S0304-4076(98)00057-8

California Governor's Office, 2013. 2013 ZEV Action Plan. Sacramento, CA.

California Plug-In Electric Vehicle Collaborative, 2015. PEV Sales Dashboard [WWW Document]. URL http://www.pevcollaborative.org/pev-sales-dashboard (accessed 10.13.15).

CARB, 2011. Low Carbon Fuel Standard: Question and Answer Guidance Document (Version 1.0).

CARB, 2009. Attachment B - 2050 Greenhouse Gas Emissions Analysis: Staff Modeling in Support of the Zero Emission Vehicle Regulation.

Carrillo-Hermosilla, J., 2006. A policy approach to the environmental impacts of technological lock-in. Ecol. Econ. 58, 717–742.

CCR, 2015. The California Low-Emission Vehicle Regulations. California.

CCR, 2010. Low Carbon Fuel Standard. California.

Center for Climate and Energy Solutions, 2013. ZEV Program [WWW Document]. URL http://www.c2es.org/us-states-regions/policy-maps/zev-program (accessed 5.14.15).

CFR, 2012. 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards. United States.

Cobb, J., 2015. Californians Bought More Plug-in Cars Than China Last Year [WWW Document]. HybridCars.com. URL http://www.hybridcars.com/californians-bought-more-plug-in-cars-than-china-last-year/ (accessed 5.11.15).

Collantes, G., Sperling, D., 2008. The origin of California's zero emission vehicle mandate. Transp. Res. Part A Policy Pract. 42, 1302–1313.

Dagsvik, J.K., Wennemo, T., Wetterwald, D.G., Aaberge, R., 2002. Potential demand for alternative fuel vehicles. Transp. Res. Part B Methodol. 36, 361–384. doi:http://dx.doi.org/10.1016/S0965-8564(01)00013-1

Dargay, J., Gately, D., Sommer, M., 2007. Vehicle Ownership and Income Growth, World wide: 1960--2030. Energy J. 28, 1–32.

Daziano, R.A., Bolduc, D., 2013. Incorporating pro-environmental preferences towards green automobile technologies through a Bayesian hybrid choice model.

de Bruijn, T.J.N.M., Norberg-Bohm, V., 2001. Voluntary, collaborative, and information-based policies: lessons and next steps for environmental and energy policy in the United States and Europe.

Dixon, L., Porche III, I.R., Kulick, J., 2002. Driving Emissions to Zero: Are the Benefits of California's Zero Emission Vehicle Program Worth the Costs? Santa Monica, CA: RAND Corporation.

Duke, R., Kammen, D.M., 1999. The Economics of Energy Market Transformation Programs. Energy J. 20, 15–64. doi:10.2307/41326186

Duvall, M., Knipping, E., Alexander, M., Tonachel, L., Clark, C., 2007. Environmental assessment of plug-in hybrid electric vehicles. EPRI, July.

EC, 2014. Regulation (EU) No 333/2014 of the European Parliament and of the Council of 11 March 2014 amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to reduce CO 2 emissions from new passenger cars. European Commission.

Eppstein, M.J., Grover, D.K., Marshall, J.S., Rizzo, D.M., 2011. An agent-based model to study market penetration of plug-in hybrid electric vehicles. Energy Policy 39, 3789–3802. doi:http://dx.doi.org/10.1016/j.enpol.2011.04.007

EU Powertrain Coalition, McKinsey & Company, 2010. A portfolio of power-trains for Europe: a fact-based analysis: The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles.

Ewing, G., Sarigollu, E., 2000. Assessing Consumer Preferences for Clean-Fuel Vehicles: A Discrete Choice Experiment. J. Public Policy Mark. 19, 106–118.

Ferrara, I., 2007. Automobile quality choice under pollution control regulation. Environ. Resour. Econ. 38, 353–372. doi:10.1007/s10640-006-9074-3

Field, B.C., Olewiler, N.D., 2011. Environmental Economics. Third Canadian Edition. Toronto, Ontario.

Fischer, C., Newell, R.G., 2008. Environmental and technology policies for climate mitigation. J. Environ. Econ. Manage. 55, 142–162. doi:10.1016/j.jeem.2007.11.001

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

Fox, J., 2013. Picking Winners : Assessing the Costs of Technology - Specific Climate Policy for U.S. Passenger Vehicles.

Friedman, L., Tanaka, M., Ida, T., Murakami, K., 2013. Consumers' Willingness to Pay for Alternative Fuel Vehicles: Comparative Analysis Between US and Japan (No. GSPP13-001). Berkeley.

Gordon, D., Sperling, D., Livingston, D., 2012. Policy Priorities for Advancing the U.S. Electric Vehicle Market. Carnegie Pap. September.

Government of California, Government of British Columbia, Government of Oregon, Government of Washington, 2013. Pacific Coast Action Plan on Climate and Energy [WWW Document]. URL http://www.pacificcoastcollaborative.org/Documents/Pacific Coast Climate Action Plan.pdf

Greenblatt, J.B., 2015. Modeling California policy impacts on greenhouse gas emissions. Energy Policy 78, 158–172. doi:10.1016/j.enpol.2014.12.024

Greene, D.L., 2001. TAFV Alternative Fuels and Vehicles Choice Model Documentation.

Greene, D.L., Park, S., Liu, C., 2014a. Public policy and the transition to electric drive vehicles in the U.S.: The role of the zero emission vehicles mandates. Energy Strateg. Rev. 5, 66–77. doi:10.1016/j.esr.2014.10.005

Greene, D.L., Park, S., Liu, C., 2014b. Analyzing the transition to electric drive vehicles in the U.S. Futures 58, 34–52. doi:10.1016/j.futures.2013.07.003

Hannisdahl, O.H., Malvik, H.V., Wensaas, G.B., 2013. The future is electric! The EV revolution in Norway – explanations and lessons learned, in: EVS27 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium.

Horne, M., Jaccard, M., Tiedemann, K., 2005. Improving behavioral realism in hybrid energy-economy models using discrete choice studies of personal transportation decisions. Energy Econ. 27, 59–77. doi:10.1016/j.eneco.2004.11.003

Hourcade, J.-C., Jaccard, M., Bataille, C., Ghersi, F., 2006. Hybrid Modeling: New Answers to Old Challenges Introduction to the Special Issue of “The Energy Journal.” Energy J. 27, 1–11. doi:10.2307/23297043

Hymel, K.M., Small, K.A., Van Dender, K., 2010. Induced demand and rebound effects in road transport. Transp. Res. Part B Methodol. 44, 1220–1241.

IEA, 2007. Fuel Cells, IEA Energy Technology Essentials.

IHS Automotive, 2015. Electric vehicle registrations by core based statistical area.

Jaccard, M., 2009. Combining Top Down and Bottom Up in Energy Economy Models, in: Evans, J., Hunt, L.C. (Eds.), International Handbook on the Economics of Energy. Edward Elgar, Northampton, pp. 311–331.

Jaccard, M., Murphy, R., Rivers, N., 2004. Energy–environment policy modeling of endogenous technological change with personal vehicles: combining top-down and bottom-up methods. Ecol. Econ. 51, 31–46. doi:10.1016/j.ecolecon.2004.06.002

Jaccard, M., Nyboer, J., Bataille, C., Sadownik, B., 2003. Modeling the cost of climate policy: distinguishing between alternative cost definitions and long-run cost dynamics. Energy J. 24, 49–73.

Jaffe, A.B., Newell, R.G., Stavins, R.N., 2005. A tale of two market failures: Technology and environmental policy. Ecol. Econ. 54, 164–174.

Kalhammer, F.R., Kopf, B.M., Swan, D.H., Roan, V.P., Walsh, M.P., 2007. Status and Prospects for Zero Emissions Vehicle Technology Report of the ARB Independent Expert Panel 2007.

Kelly, J.C., MacDonald, J.S., Keoleian, G. a., 2012. Time-dependent plug-in hybrid electric vehicle charging based on national driving patterns and demographics. Appl. Energy 94, 395–405. doi:10.1016/j.apenergy.2012.02.001

Kromer, M.A., Heywood, J.B., 2007. Electric Powertrains: Opportunities and Challenges in the US Light-Duty Vehicle Fleet.

Kyle, P., Kim, S.H., 2011. Long-term implications of alternative light-duty vehicle technologies for global greenhouse gas emissions and primary energy demands. Energy Policy 39, 3012–3024. doi:10.1016/j.enpol.2011.03.016

Larson, P.D., Viáfara, J., Parsons, R. V., Elias, A., 2014. Consumer attitudes about electric cars: Pricing analysis and policy implications. Transp. Res. Part A Policy Pract. 69, 299–314. doi:10.1016/j.tra.2014.09.002

Lieven, T., Mühlmeier, S., Henkel, S., Waller, J.F., 2011. Who will buy electric cars? An empirical study in Germany. Transp. Res. Part D Transp. Environ. 16, 236–243. doi:http://dx.doi.org/10.1016/j.trd.2010.12.001

Lu, S., 2006. Vehicle Survivability and Travel Mileage Schedules. Springfield, VA.

Lutsey, N., 2015. The EV future—already here, just not evenly distributed yet? Int. Counc. Clean Transp. Blog.

Lutsey, N., Searle, S., Chambliss, S., Bandivadekar, A., 2015. Assessment of leading electric vehicle promotion activities in United States cities. Washington DC, USA.

Marshall, B.M., Kelly, J.C., Lee, T.-K., Keoleian, G.A., Filipi, Z., 2013. Environmental assessment of plug-in hybrid electric vehicles using naturalistic drive cycles and vehicle travel patterns: A Michigan case study. Energy Policy 58, 358–370. doi:10.1016/j.enpol.2013.03.037

Mau, P., Eyzaguirre, J., Jaccard, M., Collins-Dodd, C., Tiedemann, K., 2008. The “neighbor effect”: simulating dynamics in consumer preferences for new vehicle technologies. Ecol. Econ. 68, 504–516. doi:10.1016/j.ecolecon.2008.05.007

McFadden, D., Train, K., 2000. Mixed MNL models for discrete response. J. Appl. Econom. 15, 447–470. doi:10.1002/1099-1255(200009/10)15:5<447::AID-JAE570>3.0.CO;2-1

Morgan, M.G., Henrion, M., 1990. Uncertainty: a guide to dealing with uncertainty in quantitative risk and policy analysis, Cambridge,. ed. Cambridge University Press.

Moxnes, E., 2004. Estimating customer utility of energy efficiency standards for refrigerators. J. Econ. Psychol. 25, 707–724. doi:10.1016/S0167-4870(03)00072-2

Mundaca, L., Neij, L., Worrell, E., McNeil, M., 2010. Evaluating Energy Efficiency Policies with Energy-Economy Models. Annu. Rev. Environ. Resour. 35, 305–344. doi:10.1146/annurev-environ-052810-164840

Murphy, R., Jaccard, M., 2011. Energy efficiency and the cost of GHG abatement: A comparison of bottom-up and hybrid models for the US. Energy Policy 39, 7146–7155. doi:10.1016/j.enpol.2011.08.033

Musti, S., Kockelman, K.M., 2011. Evolution of the household vehicle fleet: Anticipating fleet composition, PHEV adoption and GHG emissions in Austin, Texas. Transp. Res. Part A Policy Pract. 45, 707–720. doi:http://dx.doi.org/10.1016/j.tra.2011.04.011

New Car Dealers of BC, 2015. CEV for BC: Clean Energy Vehicle Program [WWW Document]. URL https://www.cevforbc.ca/clean-energy-vehicle-program (accessed 10.13.15).

Nordhaus, W., 2011. Designing a friendly space for technological change to slow global warming. Energy Econ. 33, 665–673.

Norton, B., Costanza, R., Bishop, R.C., 1998. The evolution of preferences: whysovereign’preferences may not lead to sustainable policies and what to do about it. Ecol. Econ. 24, 193–211.

NRC, 2013. Transitions to Alternative Vehicles and Fuels. The National Academies Press, Washington, D.C.

Nykvist, B., Nilsson, M., 2015. Rapidly falling costs of battery packs for electric vehicles. Nat. Clim. Chang. 5, 329–332.

O’Dell, J., 2002. Car Companies Team Up to Fight State’s ZEV Rule. LA Times.

Offer, G.J.J., Howey, D., Contestabile, M., Clague, R., Brandon, N.P.P., 2010. Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. Energy Policy 38, 24–29. doi:10.1016/j.enpol.2009.08.040

Ostrom, E., 1992. Policy analysis of collective action and self-governance, in: Dunn, W.N., Kelly, R.M. (Eds.), Advances in Policy Studies since 1950. Transaction Publishers, New Brunswick, New Jersey, pp. 81–119.

Ozaki, R., Sevastyanova, K., 2011. Going hybrid: An analysis of consumer purchase motivations. Energy Policy 39, 2217–2227. doi:10.1016/j.enpol.2010.04.024

P.C. 2014-935, 2014. Regulations Amending the Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations, Canada Gazette, Part I. Canada.

Paul, B., Kockelman, K., Musti, S., 2011. The Light-duty-vehicle Fleet’s Evolution: Anticipating PHEV Adoption and Greenhouse Gas Emissions Across the US Fleet.

Peters, J., 2006. The road ahead for energy-economy policy models: Integrating market dynamics, expectations and welfare costs. Simon Fraser University.

Plötz, P., Gnann, T., Wietschel, M., Paper, W., Sustainability, W.P., 2014. Modelling market diffusion of electric vehicles with real world driving data. Part I: Model structure and validation.

Potoglou, D., Kanaroglou, P.S., 2007. Household demand and willingness to pay for clean vehicles. Transp. Res. Part D Transp. Environ. 12, 264–274. doi:10.1016/j.trd.2007.03.001

Province of British Columbia, 2014. Backgrounder: BC Hydro Rates [WWW Document]. URL http://www.newsroom.gov.bc.ca/downloads/Backgrounder_BC_Hydro_Rates.pdf (accessed 7.11.15).

Rasouli, S., Timmermans, H., 2013. Influence of Social Networks on Latent Choice of Electric Cars: A Mixed Logit Specification Using Experimental Design Data. Networks Spat. Econ. 1–32. doi:10.1007/s11067-013-9194-6

Rhodes, E., Axsen, J., Jaccard, M., 2014. Does climate policy require well-informed citizen support? Glob. Environ. Chang. 29, 1–43. doi:10.1016/j.gloenvcha.2014.09.001

Rivers, N., Jaccard, M., 2006. Useful models for simulating policies to induce technological change. Energy Policy 34, 2038–2047. doi:10.1016/j.enpol.2005.02.003

Rivers, N., Jaccard, M., 2005. Combining Top-Down and Bottom-Up Approaches To Energy-Economy Modeling Using Discrete Choice Methods. Energy J. 26, 83–106. doi:10.2307/41323052

Samaras, C., Meisterling, K., 2008. Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy. Environ. Sci. Technol. 42, 3170–3176. doi:10.1021/es702178s

Santini, D.J., Vyas, A.D., 2005. Suggestions for a new vehicle choice model simulating advanced vehicles introduction decisions (Avid): Structure and Coefficients, Center for Transportation Analysis, Argonne National Laboratory. ANL/ESD/05-1.

SBC, 2010. Clean Energy Act. 2010 Legislative Session: 2nd Session, 39th Parliament, British Columbia.

SBC, 2008. Greenhouse Gas Reduction (Renewable and Low Carbon Fuel Requirements) Act. British Columbia.

SBC, 2007. Greenhouse Gas Reduction Targets Act. British Columbia.

Schoots, K., Kramer, G.J., van der Zwaan, B.C.C., 2010. Technology learning for fuel cells: An assessment of past and potential cost reductions. Energy Policy 38, 2887–2897. doi:10.1016/j.enpol.2010.01.022

Shepherd, S., Bonsall, P., Harrison, G., 2012. Factors affecting future demand for electric vehicles: A model based study. Transp. Policy 20, 62–74. doi:http://dx.doi.org/10.1016/j.tranpol.2011.12.006

Shin, J., Hong, J., Jeong, G., Lee, J., 2012. Impact of electric vehicles on existing car usage: A mixed multiple discrete–continuous extreme value model approach. Transp. Res. Part D Transp. Environ. 17, 138–144. doi:http://dx.doi.org/10.1016/j.trd.2011.10.004

Siders, D., White, J.B., 2015. Jerry Brown, Kevin de Leon abandon legislative push to require 50 percent cut in gasoline use. Sacramento Bee.

Sierzchula, W., Bakker, S., Maat, K., van Wee, B., 2014. The influence of financial incentives and other socio-economic factors on electric vehicle adoption. Energy Policy 68, 183–194. doi:10.1016/j.enpol.2014.01.043

Small, K.A., 2012. Energy policies for passenger motor vehicles. Transp. Res. Part A Policy Pract. 46, 874–889.

Small, K.A., Van Dender, K., 2007. Fuel efficiency and motor vehicle travel: the declining rebound effect. Energy J. 25–51.

Sperling, D., Eggert, A., 2014. California's climate and energy policy for transportation. Energy Strateg. Rev. 5, 88–94. doi:10.1016/j.esr.2014.10.001

Stephan, C.H., Sullivan, J., 2008. Environmental and Energy Implications of Plug-In Hybrid-Electric Vehicles. Environ. Sci. Technol. 42, 1185–1190. doi:10.1021/es062314d

Stern, N., 2007. The economics of climate change: the Stern review. cambridge University press.

Stevens, M., 2015. Electric Vehicle Sales in Canada: June 2015 Update. FleetCarma.

Struben, J., Sterman, J.D., 2008. Transition challenges for alternative fuel vehicle and transportation systems. Environ. Plan. B Plan. Des. 35, 1070–1097. doi:10.1068/b33022t

The Nordic Page, 2015. Can Norway's Electric Car Success Be a Model for World? - The Nordic Page - Economy.

Train, K., 1985. Discount rates in consumers' energy-related decisions: a review of the literature. Energy 10, 1243–1253.

U.S. EIA, 2014. Annual Energy Outlook 2014. Washington DC, USA.

U.S. EPA, 2015. California Waiver Federal Register Notices [WWW Document]. URL http://www.epa.gov/otaq/cafr.htm (accessed 5.14.15).

U.S. EPA, 2012a. Regulatory Impact Analysis: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards.

U.S. EPA, 2012b. EPA and NHTSA Set Standards to Reduce Greenhouse Gases and Improve Fuel Economy for Model Years 2017-2025 Cars and Light Trucks.

van der Vooren, A., Alkemade, F., Hekkert, M.P., 2012. Effective public resource allocation to escape lock-in: the case of infrastructure-dependent vehicle technologies. Environ. Innov. Soc. Transitions 2, 98–117.

van der Vooren, A., Brouillat, E., 2013. Evaluating CO2 reduction policy mixes in the automotive sector. Environ. Innov. Soc. Transitions. doi:10.1016/j.eist.2013.10.001

Vergis, S., Chen, B.S., 2014. Understanding Variations in U.S. Plug-In Electric Vehicle Markets.

Vergis, S., Mehta, V., 2012. Technology innovation and policy - A case study of the California ZEV mandate, in: Nilsson, M., Hillman, K., Rickne, A., Magnusson, T. (Eds.), Paving the Road to Sustainable Transport: Governance and Innovation in Low-Carbon Vehicles. Routledge, New York, NY, p. 306.

Vergis, S., Turrentine, T.S., Fulton, L., Fulton, E., 2014. Plug-In Electric Vehicles: A Case Study of Seven Markets.

Voelcker, J., 2015. Why Electric Cars Are Rare Outside CA: Arcane “Travel Provision” Rule [WWW Document]. Green Car Reports. URL http://www.greencarreports.com/news/1098525_why-electric-cars-are-rare-outside-ca-arcane-travel-provision-rule (accessed 6.15.15).

Walther, G., Wansart, J., Kieckhäfer, K., Schnieder, E., Spengler, T.S., 2010. Impact assessment in the automotive industry : mandatory market introduction of alternative powertrain technologies. Syst. Dyn. Rev. 26, 239–261. doi:10.1002/sdr

Wansart, J., Schnieder, E., 2010. Modeling market development of electric vehicles, in: 2010 IEEE International Systems Conference. IEEE, pp. 371–376. doi:10.1109/SYSTEMS.2010.5482453

Wei, M., Nelson, J.H., Greenblatt, J.B., Mileva, A., Johnston, J., Ting, M., Yang, C., Jones, C., McMahon, J.E., Kammen, D.M., 2013. Deep carbon reductions in California require electrification and integration across economic sectors. Environ. Res. Lett. 8, 014038. doi:10.1088/1748-9326/8/1/014038

Weiss, M., Patel, M.K., Junginger, M., Perujo, A., Bonnel, P., van Grootveld, G., 2012. On the electrification of road transport - Learning rates and price forecasts for hybrid-electric and battery-electric vehicles. Energy Policy 48, 374–393. doi:10.1016/j.enpol.2012.05.038

Wesseling, J.H., Farla, J.C.M., Hekkert, M.P., 2015. Exploring car manufacturers’ responses to technology-forcing regulation: The case of California's ZEV mandate. Environ. Innov. Soc. Transitions. doi:10.1016/j.eist.2015.03.001

Williams, J.H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., Morrow, W.R., Price, S., Torn, M.S., 2012. The technology path to deep greenhouse gas emissions cuts by 2050: the pivotal role of electricity. Science 335, 53–9. doi:10.1126/science.1208365

Yang, C., 2013. Fuel electricity and plug-in electric vehicles in a low carbon fuel standard. Energy Policy 56, 51–62. doi:10.1016/j.enpol.2012.05.006

Yang, C., Yeh, S., Zakerinia, S., Ramea, K., McCollum, D., 2015. Achieving California's 80% greenhouse gas reduction target in 2050: Technology, policy and scenario analysis using CA-TIMES energy economic systems model. Energy Policy 77, 118–130. doi:10.1016/j.enpol.2014.12.006

Yang, S., Allenby, G.M., 2003. Modeling interdependent consumer preferences. J. Mark. Res. 40, 282–294.

Zhang, T., Gensler, S., Garcia, R., 2011. A Study of the Diffusion of Alternative Fuel Vehicles: An Agent-Based Modeling Approach*. J. Prod. Innov. Manag. 28, 152–168. doi:10.1111/j.1540-5885.2011.00789.x

ZSW - Centre for Solar Energy and Hydrogen Research Baden-Wurttemberg, 2015. More than 740,000 Cars Worldwide Powered by Electricity [WWW Document]. URL http://www.zsw-bw.de/en/support/news/news-detail/mehr-als-740000-autos-weltweit-fahren-mit-strom.html (accessed 5.14.15).

Appendix.

Regional-Global Intangible Cost Split Literature Review Resources

Table A.1 Studies and attributes reviewed to determine regional-global intangible cost split

Study	Methodology	Non-financial attributes affecting vehicle purchase decisions
Greene et al., 2014a	hybrid vehicle and fuels model	range, range anxiety, fuel availability, refueling time, innovation, model diversity
Greene et al., 2014b	hybrid vehicle and fuels model	HFCVs: model diversity, market share majority, fuel availability, refueling time, range, BEVs: model diversity, market share majority, fuel availability, range anxiety, range
Larson et al., 2014	stated preference survey	electric vehicle: reliability, range, charging station access, long recharge time, size or style availability, need to recharge battery
Plötz et al., 2014	preference survey and agent-based model	size, safety, brand, design, fuel consumption, gear shift, fuel type, four-wheel drive, power, emissions, acceleration
Daziano and Bolduc, 2013	hybrid energy economy model	vehicle type/class, alternative fuel vehicle constant, HEV constant, HFCV constant, fuel availability, HOV lane access, power
Friedman et al., 2013	mixed logit model	cheaper fuel than gasoline, range, emissions reduced, fuel station availability
Rasouli and Timmermans, 2013	mixed logit model	cruising range, charge time, maximum speed, distance to recharge station
van der Vooren and Brouillat, 2013	agent-based model	affordability of vehicle, affordability of driving, refueling availability, market share of firm (popularity), energy capacity (range), cleanness, quality, brand
Shepherd et al., 2012	system dynamics model	awareness – exposure and memory based on marketing and word of mouth, marketing, maximum speed, fuel availability, emissions, range
Shin et al., 2012	discrete choice model	diesel constant, HEV constant, BEV constant, refueling infrastructure
Eppstein et al., 2011	spatially-explicit agent-based model	range, ability to accurately assess fuel costs, comfort with technology, reasons to save on gasoline – rational financial vs. other
Lieven et al., 2011	stated preference survey	range, performance, durability, environment, convenience
Musti and Kockelman, 2011	stated preference survey and microsimulation model	reliability, vehicle type/class, cabin room / interior size, overall visual appeal, amenities, perceived resale value, other

Study	Methodology	Non-financial attributes affecting vehicle purchase decisions
Ozaki and Sevastyanova, 2011	stated preference survey	environment, new technology, socially responsible, available incentives, comfort and quality, technology, social preferences, reliability and brand, design, size
Paul et al., 2011	revealed and stated preference surveys and microsimulation model	vehicle type, interior size, other, attractiveness, amenities, perceived resale value, safety, transmission type
Zhang et al., 2011	agent-based model	sedan, sports utility vehicle, gasoline, HEV, PHEV, BEV, miles per gallon, battery range
Walther et al., 2010	dynamic simulation model	awareness, range, recharge availability, installed base of vehicles
Wansart and Schnieder, 2010	system dynamics model	recharging stations, awareness – exposure and memory based on marketing and word of mouth, installed base of BEVs, range, electric vehicle constant
Alvarez-Daziano and Bolduc, 2009	hybrid energy economy model	vehicle type/class, alternative fuel vehicle constant, HEV constant, HFCV constant, fuel availability, HOV lane access, power
Axsen et al., 2009	stated and revealed preference survey and joint modelling techniques	horsepower, vehicle size (other than small), vehicle type (other than car), HEV
Bhat et al., 2009	multinomial logit model	seat capacity vs. household size, luggage volume, horsepower, engine size, GHGs, premium fuel
Bolduc et al., 2008	hybrid energy economy model	vehicle type/class, alternative fuel vehicle constant, HEV constant, HFCV constant, fuel availability, HOV lane access, power
Mau et al., 2008	discrete choice survey and model	cruising range, warranty coverage, gasoline vehicle constant, refuelling station coverage, HFCV constant
Struben and Sterman, 2008	dynamic simulation model	performance, operating boost, safety, range, ecological impact
Potoglou and Kanaroglou, 2007	nested multinomial logit model	HEV constant, alternative fuel vehicle constant, large constant, compact constant, midsize constant, van constant, sports utility vehicle constant, pick-up truck constant, acceleration, fuel availability, HOV lane access, pollution
Horne et al., 2005	discrete choice survey	proportion of stations with proper fuel, express lane access, emissions, power, gasoline constant, alternative fuel constant, HEV constant
Santini and Vyas, 2005	stated and revealed preference survey	range, home recharging capability, fuel availability, top speed, acceleration, luggage space, battery capacity, PHEV constant, criteria air contaminant emissions, make/model diversity, HOV lane access

Study	Methodology	Non-financial attributes affecting vehicle purchase decisions
Dagsvik et al., 2002	stated preference survey	age, gender, top speed, driving range, fuel efficiency, electric vehicle, HEV constant, propane, taste persistence
Greene, 2001	nested multinomial logit model	range, acceleration, home refueling access, luggage space, fuel availability, make/model availability
Brownstone et al., 2000	stated and revealed preference with multinomial and mixed logit models	acceleration, top speed, range, pollution, truck, sports utility vehicles, van, mini sports utility, small car, sports car, luxury, import, new vehicle, used vehicle, fuel station availability, station wagon, electric vehicle, compressed natural gas, methanol
Ewing and Sarigollu, 2000	discrete choice survey	acceleration, cruising range, refueling rate, polluting emissions, alternative fuel constant, electric constant
McFadden and Train, 2000	mixed multinomial logit model	range, acceleration, top speed, pollution, size, ‘big enough’, luggage space, fuel station availability, sports utility vehicle, sports car, station wagon, truck, van, electric vehicle, compressed natural gas, methanol
Brownstone and Train, 1998	stated preference and mixed logit model	range, acceleration, top speed, pollution, size, ‘big enough’, luggage space, fuel station availability, sports utility vehicle constant, sports car, station wagon, truck, van, electric vehicle, compressed natural gas, methanol

Low Carbon Fuel Standard and Corporate Average Fuel Economy Standard Policy Details

Table A.2 Low carbon fuel standard (LCFS) scenarios using electricity from British Columbia

Reference Case LCFS								
Fuel	**well-to-wheel GHG intensity (tCO_2e/GJ)**							
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gasoline	0.0882	0.0882	0.0878	0.0851	0.0851	0.0851	0.0851	0.0851
Diesel	0.0827	0.0827	0.0823	0.0797	0.0797	0.0797	0.0797	0.0797
Ethanol*	0.0777	0.0777	0.0773	0.0748	0.0748	0.0748	0.0748	0.0748
Electricity*	0.0078	0.0064	0.0061	0.0059	0.0059	0.0060	0.0060	0.0060
Hydrogen	0.0936	0.0936	0.0936	0.0936	0.0936	0.0936	0.0936	0.0936

Medium Stringency LCFS								
Fuel	**well-to-wheel GHG intensity (tCO_2e/GJ)**							
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gasoline	0.0882	0.0882	0.0878	0.0851	0.0817	0.0775	0.0765	0.0756
Diesel	0.0827	0.0827	0.0823	0.0797	0.0766	0.0727	0.0717	0.0709
Ethanol*	0.0777	0.0777	0.0773	0.0748	0.0719	0.0682	0.0673	0.0665
Electricity*	0.0078	0.0064	0.0064	0.0052	0.0046	0.0040	0.0034	0.0028
Hydrogen	0.0936	0.0936	0.0936	0.0936	0.0916	0.0889	0.0695	0.0577

High Stringency LCFS								
Fuel	**Well-to-wheel GHG intensity (tCO_2e/GJ)**							
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gasoline	0.0882	0.0882	0.0878	0.0849	0.0816	0.0774	0.0749	0.0698
Diesel	0.0827	0.0827	0.0823	0.0796	0.0765	0.0725	0.0702	0.0654
Ethanol*	0.0777	0.0777	0.0772	0.0747	0.0718	0.0681	0.0659	0.0614
Electricity*	0.0078	0.0064	0.0064	0.0052	0.0046	0.0040	0.0034	0.0028
Hydrogen	0.0936	0.0936	0.0936	0.0936	0.0897	0.0842	0.0454	0.0218

*Like Fox (2013) I assume ethanol vehicles run on a mix of 85% ethanol and 15% gasoline. I assume PHEVs use electricity 66% of the time and gasoline 34% of the time (based on Kelly et al., 2012; Marshall et al., 2013).

Table A.3 Corporate average fuel economy (CAFE) standard scenarios

Reference Case CAFE Standard

Vehicle Technology	fuel efficiency (GJ/km)							
	2015	2020	2025	2030	2035	2040	2045	2050
Gasoline	0.003297	0.002779	0.002170	0.002158	0.002156	0.002160	0.002160	0.002160
Diesel	0.003208	0.002954	0.002470	0.002462	0.002461	0.002464	0.002464	0.002464
Ethanol*	0.004397	0.003709	0.002931	0.002862	0.002858	0.002862	0.002862	0.002862
HEV	0.002240	0.001928	0.001660	0.001660	0.001660	0.001660	0.001660	0.001660
PHEV*	0.001337	0.001205	0.001006	0.001003	0.001003	0.001004	0.001004	0.001004
BEV	0.001097	0.001030	0.000950	0.000972	0.000979	0.000983	0.000983	0.000983
HFCV	0.001398	0.001313	0.001211	0.001238	0.001248	0.001252	0.001252	0.001252

Medium Stringency CAFE Standard

Vehicle Technology	fuel efficiency (GJ/km)							
	2015	2020	2025	2030	2035	2040	2045	2050
Gasoline	0.003083	0.002627	0.002170	0.001714	0.001601	0.001488	0.001374	0.001261
Diesel	0.002954	0.002517	0.002080	0.001642	0.001534	0.001425	0.001317	0.001208
Ethanol*	0.004144	0.003521	0.002918	0.002312	0.002159	0.002006	0.001854	0.001701
HEV	0.002164	0.001890	0.001617	0.001344	0.001242	0.001140	0.001038	0.000936
PHEV*	0.001180	0.001018	0.000843	0.000689	0.000649	0.000605	0.000560	0.000516
BEV	0.001031	0.000964	0.000898	0.000832	0.000786	0.000741	0.000696	0.000650
HFCV	0.001304	0.001209	0.001115	0.001020	0.000953	0.000885	0.000817	0.000750

High Stringency CAFE Standard

Vehicle Technology	fuel efficiency (GJ/km)							
	2015	2020	2025	2030	2035	2040	2045	2050
Gasoline	0.003025	0.002511	0.001997	0.001483	0.001361	0.001240	0.001119	0.000997
Diesel	0.002898	0.002406	0.001913	0.001420	0.001304	0.001188	0.001072	0.000956
Ethanol*	0.004080	0.003386	0.002693	0.002000	0.001836	0.001672	0.001509	0.001345
HEV	0.002113	0.001788	0.001464	0.001139	0.001034	0.000929	0.000823	0.000718
PHEV*	0.001156	0.000971	0.000784	0.000600	0.000553	0.000506	0.000458	0.000411
BEV	0.001003	0.000909	0.000815	0.000721	0.000675	0.000628	0.000581	0.000534
HFCV	0.001263	0.001128	0.000993	0.000858	0.000795	0.000731	0.000668	0.000604

*Ethanol vehicle and PHEV fuel efficiencies are based on assumed fuel splits noted under Table A.2.