Simulating the Role of Recharging and Refuelling Infrastructure in the Uptake of Zero Emission Vehicles in Canada

by

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Abstract

Although widespread uptake of zero emission vehicles (ZEVs) (including battery electric, plug-in hybrid, and hydrogen fuel cell vehicles) could help Canada achieve deep greenhouse gas reductions targets, many barriers currently prevent their proliferation in the vehicle market. Deployment of charging and refuelling infrastructure is widely claimed to support ZEV uptake; but studies have differed in their estimates regarding the extent to which ZEV infrastructure deployment might increase ZEV sales. A particular limitation among such studies is a lack of empirical basis, and limited representation of the various charging and refuelling options. Using survey data collected from 1,884 Canadian new vehicle-buying households in 2017, I develop a version of a behaviourally realistic market forecasting model, the Respondent-based Preferences and Constraints model (REPAC), to investigate the extent to which infrastructure deployment can boost ZEV sales in Canada. I simulate the impacts of increasing the availability of home, work, public destination, and highway charging access on plug-in electric vehicles sales, and the impacts of increasing hydrogen refuelling stations on hydrogen fuel cell vehicle sales. Results suggest that new ZEV market share in Canada will not substantially benefit from increased infrastructure. Even when electric vehicle charging access and hydrogen fueling access are simulated to reach “universally” available levels by 2030, new ZEV market share does not rise by more than 1.5 percentage points above the business as usual trajectory. On the other hand, REPAC simulates ZEV market share rising as high as 30% with strong ZEV-supportive policies, even without the addition of charging or refueling infrastructure above business as usual levels. These findings suggest that to achieve ambitious long-term ZEV sale targets, a comprehensive suite of policies is likely required, particularly including those that induce increased availability of ZEVs.

Keywords: Zero emission vehicle; infrastructure; charging; refuelling; REPAC model; access,

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List of Acronyms

BEV	Battery electric vehicle
CV	Conventional vehicle
CZEVS	Canadian Zero Emission Vehicle Survey
DC	Direct current
GHG	Greenhouse gas
HEV	Hybrid electric vehicle
HFCV	Hydrogen fuel cell vehicle
IEA	International Energy Agency
LCM	Latent class model
MSRP	Manufacturer suggested retail price
OEM	Original equipment manufacturer
PEV	Plug-in electric vehicle
PHEV	Plug-in hybrid electric vehicle
REPAC	Respondent-based Preferences and Constraints
RP	Revealed preference
SFU	Simon Fraser University
SP	Stated preference
START	Sustainable Transportation Action Research Team
US	United States
ZEV	Zero emission vehicle

Chapter 1. Introduction

Transportation has been identified as an important opportunity for greenhouse gas (GHG) mitigation in support of global climate commitments (International Energy Agency, 2016). In Canada, the transportation sector accounts for 23% of GHG emissions (Environment and Climate Change Canada, 2016). Personal transportation from the use of private vehicles accounts for roughly half of the emissions from transport, and since 2011, light duty vehicle sales in Canada have been continuing to grow by roughly 5% each year (Klippenstein, 2018). Zero emission vehicles (ZEVs), which can operate without emitting any tailpipe GHGs, are emerging as a promising way to combat global climate change while maintaining the benefits of personal mobility associate with private vehicle use. My definition of ZEVs (following the governments of Canada, California and others) includes battery electric vehicles (BEVs) which are powered solely by electricity charged from the grid, plug-in hybrid electric vehicles (PHEVs) which can be powered interchangeably between electricity and gasoline (or both together), and hydrogen fuel cell vehicles (HFCVs) which are powered by hydrogen gas.

At various times, the Government of Canada has recognized the importance of transitioning towards ZEV technologies. For example, its 2010 Electric Vehicle Technology Roadmap emphasized the vision of reaching 15% new market share of plug-in electric vehicles (BEVs and PHEVs, abbreviated as PEVs) by the year 2018 (Government of Canada, 2010). However, this target lapsed with new market share for PEVs reaching only 0.9% by the end of 2017 (Klippenstein, 2018), likely due to a lack of strong policy (Axsen et al., 2016; Wolinetz & Axsen, 2017). In 2016 the Canadian government reiterated its intended support for ZEV transition in its outline of the Pan-Canadian Framework on Clean Growth and Climate Change (Government of Canada, 2016). Though, as of the writing of this research project, no unifying federal policy is yet in place to support this directive nation wide. The International Energy Agency (IEA) has since launched a new Electric Vehicles Initiative (EVI) campaign establishing 30% as the benchmark proportion of ZEV sales required by 2030 to enable deep GHG reductions in support of globally coordinated climate change mitigation (International Energy Agency, 2017). Canada, as an ascribing member to the EVI, will be evaluated on its progress toward this target.

ZEV uptake in Canada continues to grow, but slowly (Klippenstein, 2018). A number of Canada-based studies indicate that a potential market for ZEVs exists (Axsen, Bailey, & Kamiya, 2013; Axsen & Wolinetz, 2017; Ferguson et al., 2016; Mohamed et al., 2016); however, the translation of ZEV-interest into actual sales has been inhibited by the presence of many social, technical, and financial barriers (Li, Trutnevyte, & Strachan, 2015). Market demand, which considers only observed sales, is a constrained portion of overall demand for ZEVs as it reflects only the desired purchases that are not prevented by barriers. The desired but unrealized portion of ZEV demand is referred to as latent (meaning "hidden") demand (Clifton & Moura, 2016). Experts are largely in agreement that the barriers most responsible for constraining ZEV demand include consumers' limited familiarity with ZEV technologies, high upfront purchase prices, limited driving range, limited vehicle availability, and insufficient recharging and refuelling infrastructure (Egbue & Long, 2015; Eppstein et al., 2011; Lane & Potter, 2007; Rezvani, Jansson, & Bodin, 2015; Wolinetz & Axsen, 2017). For the purposes of this project, I focus my attention primarily on ZEV infrastructure access, meaning recharging access for PEVs and hydrogen refuelling station access for HFCVs.

Policies aimed at improving home, work, and public destination charging access for PEVs, and hydrogen refuelling access for HFCVs, are thought by some to be important enablers in supporting a ZEV transition (Egbue & Long, 2015; Hall & Lutsey, 2017; Hardman et al., 2018; Rezvani et al., 2015; Slowik & Lutsey, 2017). Of the studies that have quantified the impact of ZEV infrastructure provision on ZEV sales, some report substantial increases in new ZEV market share (Shafiei et al., 2012; Tran et al., 2013), while others have reported more modest results (Harrison & Thiel, 2017; Lin & Greene, 2011; Silvia & Krause, 2016). Differences in modelling techniques, behavioural representation, and the representation of infrastructure types might be factors that contribute to the inconsistency among researchers' findings. Thus, the extent to which ZEV infrastructure may support ZEV sales in Canada is not clearly understood, creating uncertainty in recommendations for policy development. The current study aims to clarify this uncertainty. With new 2017 data from the Canadian Zero Emission Vehicles Survey (CZEVS), I use empirically estimated consumer preferences and novel representation of recharging and refuelling infrastructure (differentiating among home, workplace, destination, and highway recharging access for PEVs, and hydrogen refuelling stations for HFCVs) to simulate the market impacts from various types of ZEV infrastructure provision at various levels of deployment. To ensure realistic projections of new ZEV market share, I investigate the impact of ZEV infrastructure provision given the presence of other existing constraints.

For my research, I develop a version of the Respondent-based Preferences and Constraints (REPAC) model, a behaviourally-realistic, agent-based simulation model developed by Wolinetz & Axsen, (2017), to project new ZEV market share in Canada under various policy conditions. The objectives of the present study are to determine:

1) the extent to which charging/refuelling infrastructure deployment, on its own, can increase ZEV sales in Canada, and

2) what additional policies may be needed to push ZEV sales towards 30% new ZEV market share by 2030 (as aligned with International Energy Association targets), or higher.

The output is intended to better inform strategic ZEV policy development in the Canadian context by demonstrating the potential (as well as the limitations) of ZEV infrastructure deployment in stimulating ZEV sales.

1.1. ZEV Infrastructure Types in Canada

In order to enable transportation-related GHG reductions through the use of ZEVs, sufficient recharging and refuelling infrastructure is required to power those vehicles. Both BEVs and PHEVs (collectively referred to as plug-in electric vehicles, or PEVs) require charging from the electric grid in order to offset emissions from gasoline-powered kilometers. BEVs are fully electric and are powered solely by their onboard battery, while PHEVs have an additional gas tank which allows them to drive using gasoline when their charge is low. Hydrogen fuel cell vehicles (HFCVs) require refuelling with hydrogen, which is conceptually similar to refilling a gasoline-powered vehicle, but releasing no tailpipe emissions through operation. Typically, HFCVs must be refilled at designated hydrogen refuelling stations.

For PEVs in North America, three different charging levels exist which correspond with relative charging times. Level 1 charging is the most abundantly available but it is also the slowest option. Level 1 charging can take place using electricity from any standard 110-120-volt outlet. Between 50-70% of Canadian households had access to Level 1 recharging in 2013 (Axsen et al., 2013), though fully charging a BEV this way may take longer than 48 hours for vehicles with large ranges. With Level 2 charging from a 220-240 volt outlet, a BEV can be fully recharged in 4-12 hours. Most charging stations in public locations today deliver Level 2 charging capabilities. Most houses are built with a Level 2 power source though this source may be harder to access and installing upgrades to improve usability for vehicle charging can be very expensive. Level 3 charging, also referred to as DC (direct current) fast charging, is typically not found at residential locations but may be located in some public areas and along major routes of connectivity such as highways. DC fast chargers can get a depleted BEV battery to a nearly-full charge in as little as 30 minutes.

Homes are a particularly important charging point among PEV buyers as homes are typically where vehicles are parked the most often and for the longest periods of time. The vast majority of PEV charging occurs at owners' homes (California Air Resources Board, 2017; Idaho National Laboratory, 2016). While 90% of Canadians' daily driving needs could be met with the driving range of most current electric vehicles (Clean Energy Canada, 2017), recharge availability at workplaces, public locations, and along highways can allow PEV drivers to increase travel distance beyond the range of a single charge. Charging access at workplaces and public destinations are thought to be secondary and tertiary priorities for policy support compared to home charging (Bailey, Miele, & Axsen, 2015; Figenbaum & Kolbenstvedt, 2016; Hardman et al., 2018; Lin & Greene, 2011), as PEVs are more likely to be "topped up" at these locations rather than recharged from empty.

While it is uncertain what "optimal" levels of infrastructure are needed to support ZEV use (Hardman et al., 2018), recharging and refuelling access for ZEVs in Canada is not yet abundantly available or convenient to access for many citizens. The problem of infrastructure provision for ZEVs has often been termed a "chicken and egg" problem. Infrastructure providers are reluctant to invest in expensive infrastructure projects without the security of a well-established ZEV market, yet consumers may be unwilling to purchase a ZEV unless they perceive a reliant and widespread charging or refuelling network. The case may be especially strong for HFCVs, as hydrogen fuelling stations are the only source of hydrogen fuel and are exceptionally scarce in Canada. As of 2018, there are still no publicly available (retail) hydrogen refuelling stations, and very few private hydrogen distributors (Natural Resources Canada, 2018).

All provinces have already implemented at least some degree of publicly located charging infrastructure (Axsen, Goldberg, & Melton, 2016b), though few provinces or cities have announced support for home charging improvements. British Columbia, Ontario, and Quebec are the only provinces wherein select cities offer subsidies to offset costs of upgrading home charging infrastructure, or have announced PEV charging support in new building codes.

1.2. The Relationship Between Infrastructure and ZEV Adoption: Previous Approaches and Findings

The topic of ZEV charging and refuelling infrastructure has been broadly studied in the literature (Hardman et al., 2018). Generally, many have suggested that improved ZEV infrastructure will be an important factor in encouraging the market acceptance of ZEVs (Egbue & Long, 2015; Hall & Lutsey, 2017; Neubauer & Wood, 2014; Slowik & Lutsey, 2017). Few studies have quantified the extent to which ZEV infrastructure provision may impact new market share of ZEVs, and among them, both optimistic (e.g. (Lin & Greene, 2011; Shafiei et al., 2012; Tran et al., 2013) and modest results (Harrison & Thiel, 2017; Silvia & Krause, 2016) have been reported. In this literature review I briefly describe some of the methods that have been used to estimate how ZEV infrastructure access interacts with ZEV sales, including statistical studies, regression analysis, and simulation modelling studies. I report the findings of these studies, some of their limitations, and later describe how the present study seeks to improve upon the previous methods.

Some statistical analyses have been done to investigate how infrastructure access relates to ZEV sales across different regions. A compelling observation drawn from select cities in the United States found that during the one year period between 2015 and 2016, an increase in public infrastructure between 30-80% (depending on the city) corresponded with a doubling of electric vehicle uptake or more (Slowik & Lutsey, 2017). Regression results have supported the notion that ZEV infrastructure access and

ZEV sales are statistically tied. For example, in a large, recent, statistical regression analysis, Hall and Lutsey (2017) found Level 2 and DC-fast public charging infrastructure to be statistically associated with PEV uptake across 350 international metropolitan areas. The results are also supported by Slowik & Lutsey (2017), additionally finding purchase incentives, and model availability to be key factors of ZEV uptake in the United States. Using regression as well, Sierzchula et al. (2014) found that among various financial and socio-economic factors (including education levels, income, environmental attitudes, and the presence of local PEV manufacturing facilities), charging infrastructure was found to be the best predictor of PEV market share.

A limitation of such regression analyses is that they are largely correlative. Further, they often lack depth in their analysis of behavioural motivation and causation, and so may not be great predictors of future action. A Canadian study improves upon this limitation by investigating how infrastructure access relates to mainstream consumers' interest in PEV purchase, rather than observed PEV sales. The Canada-wide regression analysis of 1739 new vehicle buyers found that the perception of abundant public charging infrastructure was weakly associated with respondents' interest in PEV uptake when controlling for other factors (Bailey et al., 2015), suggesting that the presence of ZEV infrastructure is a relatively small factor in the decision for mainstream consumers contemplating ZEV purchase.

Forward-looking projections of ZEV uptake can be created using various types of models. Simulation models can be used to simulate how various factors may influence ZEV sales in different scenarios as conditions change. Simulation models vary considerably in their structure, complexity, and representation of input parameters. Table 1 summarises a selection of ZEV adoption simulation studies conducted over the past decade for which some degree of ZEV infrastructure is represented. In addition to summarizing the specificity of infrastructure representation within these models, Table 1 also indicates other key components of the studies which can be tied to the reliability of their outputs, such as the representation of consumer behaviours, and what other barriers are considered in the market share projections.

Table 1. Infrastructure Representation in ZEV Adoption Modelling Studies

	Study :	Potoglou & Kanaroglou (2007)	Lin & Greene (2011)	Shafiei et al. (2012)	Tran et al. (2013)	Gnann et al. (2015)	Wolf et al. (2015)	Silvia & Krause (2016)	Harrison & Thiel (2017)	Brand et al. (2017)	Wolinetz & Axsen (2017)	Current study (2018)
	Isolates infra.impacts	-	✓	✓	✓	-	-	✓	✓	-	-	✓
Model details:	Model name: (model type):	N/A (choice)	MA3T (choice)	N/A (ABM)	N/A (choice)	ALADIN (ABM)	Innomind (ABM)	NetLogo (ABM)	PTTMAM (ABM)	UKTCM (ABM)	REPAC (ABM)	REPAC (ABM)
	Region of study:	Hamilton, Canada	USA	Iceland	Europe	Germany	Berlin, Germany	USA city*	European Union	UK	Canada	Canada
	Empirical behaviours:	✓	-	-	-	✓	✓	-	-	✓	✓	✓
	ZEV Types:	ZEVs (aggregate)	BEV, PHEV,	BEV	BEV, PHEV, HFCV	BEV, PHEV, BEV+	BEV	BEV	PEVs (aggregate) HFCV	BEV, PHEV, HFCV	BEV, PHEV	BEV, PHEV, HFCV
Infrastructure Representation:	Home charging:	-	✓	Aggregate	-	✓	-	✓	✓	Aggregate	✓	✓
	Workplace charging:	-	✓		-	-	-	-	✓		-	✓
	Public charging:	✓	✓		✓	-		✓	✓		-	✓
	DC fast charging:	-	-	-	-	-	-	✓	✓		-	✓
	H2 refuelling:	-	-	-	✓	-	-	-	-		-	✓
Other Barriers:	Purchase price:	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Fuel cost:	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Familiarity:	-	✓	✓	-	-	-	✓	-	✓	✓	✓
	Variety/availability:	-	✓	-	-	✓	-	-	-	✓	✓	✓
	Range:	-	✓	-	✓	✓	-	✓	-	✓	✓	✓
Modelled Policies:	Tax/exemption:	✓	-	✓	-	✓	✓	-	-	✓	✓	✓
	Subsidy/falling costs:	-	✓	-	✓	✓	✓	✓	✓	✓	✓	✓
	Infrastructure:	-	✓	✓	✓	-	(exclusive EV zone)	✓	✓	-	✓	✓
	Vehicle supply:	-	-	-	-	-	-	-	-	-	✓	✓

EV+ refers to extended-range BEV

* Hypothetical American city based off USA survey data

As per the third row in Table 1, two broad categories of models are commonly used to simulate the market diffusion of ZEVs: consumer choice models and agent-based models (ABMs). Choice models attempt to simulate how consumers make trade-offs in the process of decision making and can be used to simulate the market shares of competing technologies from the bottom-up. Typical choice models employ the neoclassical assumptions of rational choice, perfect information, and utility maximization (Jackson, 2005), meaning that among a set of transparent alternatives, consumers are assumed to select the product with the combination of attributes that satisfies them the most. Choice modelling has been widely applied to the study of ZEVs (Brownstone, Bunch, & Train, 2000; Hidrue, Parsons, Kempton, & Gardner, 2011; Potoglou & Kanaroglou, 2007; Tran, Banister, Bishop, & McCulloch, 2013). ABMs are similar to choice models in that they also seek to replicate the decisions of consumers (or other actors), though are typically more complex. ABMs can represent factors that choice models neglect, such as the presence of purchasing constraints, or interactions with other agents (Gilbert, 2008). Some ABMs simulate the actions of different types of agents in addition to consumers, such as auto manufactures, fuel producers, or governments (e.g. Harrison & Thiel, 2017; Sullivan et al., 2009). Like choice models, the quality of ABM results is tied directly to their inputs, such as the quality of the behavioural data on which the model is based, and the assumptions of other parameter values.

In a previous review of the ZEV uptake modelling literature, Al-Alawi and Bradley (2013) note the need for improved behavioural representation in models, suggesting that richer data is needed to simulate the responses of consumers. Table 1 indicates the same need in the current review, identifying few studies that have used empirically-estimated, ZEV-specific consumer preferences in their representation of consumer behaviours. Some studies in the literature have inferred consumer preferences from revealed preference (RP) data (i.e. collected through observations of decisions that individuals have carried out in the past, such as market data) (e.g. Axsen et al., 2009; Brownstone et al., 2000). However, because ZEVs are such new technologies, long term sales data may not be available to reliably inform such inferences. Other studies have used stated preference (SP) data which describes what respondents say they want rather than what has been revealed through actions. Methods for SP data collection include surveying and stated choice experiments[2]. A strength of SP data is its ability to represent hypothetical market conditions for new technologies that have not fully emerged in the market, such as ZEVs. Further, they can allow for a very detailed collection of preferences for the individual attributes of a technology (Axsen et al., 2009). However, due to the hypothetical nature of SP data, models that rely solely on SP inputs can produce results that deviate from true market behaviour (Allenby et al., 2005). Thus, it is important that SP methods are carefully designed to reduce biases.

While it is not represented in Table 1, the representation of consumer heterogeneity is another factor that can improve the behavioural realism in ZEV adoption simulation studies. Recent studies by Brand, Cluzel, & Anable, (2017) and Axsen et al., (2015) suggest that the new vehicle market is diverse and that ZEV purchases are motivated by different factors among individuals (Axsen et al., 2015). Incorporating consumer heterogeneity in modelling studies may be important, as Wolf et al. (2015) found that the representation of heterogeneity among agents in their model impacted the effectiveness of ZEV policy outcomes at a significant level.

The second row of Table 1 indicates which studies have isolated and quantified the impact of ZEV infrastructure provision on ZEV sales, making their results directly comparable to the present study. Five have included simulations which isolate the impact of infrastructure provision (or the elimination of charging concerns) to estimate its direct impact on ZEV sales. The findings vary from study to study. Large increases in ZEV infrastructure access are shown to increase new ZEV market share between zero percentage points (Silvia & Krause, 2016) and 20 percentage points (Shafiei et al., 2012). Reasons for this variation could be the result of differing levels of infrastructure representation, regions of study, and representation of consumers. The five studies are summarized below.

An ABM study by Silvia and Krause (2016) investigates the role of charger deployment on US PEV sales using the case study of a hypothetical (but typical) US city.

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[2] Choice experiments elicit stated preference data in the context of a hypothetical purchasing environment, where respondents are asked to choose their preferred option among competitors a series of times as the attributes for each option vary. Respondents' selections are ultimately used to determine their preferences for each attribute. The preferences are represented as coefficients that can be used to calculate a person's utility for items comprised of a collection of the assessed attributes.

The authors use methods similar to REPAC, where consumers' choices are based on preferences and are constrained by a series of criteria (assessed through both demographic and randomly assigned data). The authors find that improving charging access public locations via a $5.5 million investment has no impact on sales, whereas the same dollar investment directed at ZEV purchase subsidies could more than double ZEV sales (increasing new ZEV market share from 0.76% to 1.85%). Similarly, in Europe, Harrison & Thiel (2017) found strong subsidization of infrastructure (for infrastructure providers) to have a low impact on ZEV sales. Relative to a business as usual scenario, if infrastructure implementation becomes 100% subsidized between 2010 and 2030 (resulting in the addition of roughly two million public charging points across the European Union), the 2030 ZEV new market share rises by approximately one percentage point. In their analysis, HFCVs do not achieve any market penetration despite the 100% subsidizing of hydrogen infrastructure due to competition from PEVs. These authors summarize their findings indicating that infrastructure deployment alone is unlikely to induce large shifts in ZEV adoption.

Lin and Greene (2011) use a choice model to simulate the impact of infrastructure maximization on PEV sales in the U.S. In a simulation where home, work, and publicly located charging infrastructure reaches 100% availability by the year 2025, PEV sales are shown to increase by roughly two million vehicles compared to the baseline case. This translates to approximately 12% of American auto sales assuming that 17 million vehicles are sold annually, as was the case in 2017 (USA International Trade Administration, 2018). More optimistically, Shafiei et al., (2012) found that the elimination of charging concerns (with only aggregate representation of charging access) in Iceland could increase new BEV market share by 20 percentage points. Another European study by Tran et al., (2013), considering only public charging and hydrogen refuelling access, found that increasing ZEV infrastructure by 70% above 2013 levels can increase PEV market share by over 10 percentage points by 2030, (though with no penetration of HFCVs). The study still concludes that conventional vehicles will remain dominant in the market unless ZEV purchase prices become significantly more competitive with the incumbent technology.

Notably, the five reviewed studies may be critiqued for their behavioural realism. As shown in Table 1, none of the five described studies have used empirically-estimated consumer preferences for ZEVs in their simulations of ZEV uptake. For example, Tran et al., (2013) use probabilistic representations of consumer heterogeneity through Monte Carlo analysis rather than inferring preferences from SP or RP methods. Shafiei et al. (2012) and Silvia & Krause (2016) both use synthetic populations with assigned preferences, rather than basing agents off survey respondents whose preferences have been measured. A further limitation is that none of the above studies capture the full suite of home, work, public, and DC fast charging infrastructure along with hydrogen refuelling infrastructure. Since consumers interact differently with each type of charging and refuelling option (Hardman et al., 2018; Idaho National Laboratory, 2016; Lin & Greene, 2011), explicit representation of each type can help make market share simulations more realistic and thus provide better insights for policy makers and infrastructure providers.

One final limitation of note in the reviewed literature is the general lack of representation of supply-side characteristics, such as ZEV availability and variety (e.g. Harrison & Thiel, 2017; Silvia & Krause, 2016; Tran et al., 2013). ZEV supply has been shown to have an important impact on ZEV sales in some studies (Brand, Cluzel, & Anable, 2017; Gnann et al., 2015; Wolinetz & Axsen, 2017). Consequently, studies that neglect to model such barriers may report optimistic projections of ZEV uptake (e.g. Shafiei et al., 2012; Tran et al., 2013). Al-Alawi & Bradley (2013) suggest the need for improved representation of vehicle variety in future studies where models should include a broad variety of competing drivetrain types and vehicle classes for consumers to choose among.

The REPAC approach addresses limitations in the existing literature through the use of empirically based consumer preferences, the representation of supply side characteristics of ZEV transition, and the inclusion of other barriers to ZEV adoption. These are further detailed in the Methods section, and readers may additionally refer to a previous paper by Wolinetz and Axsen (2017). In addition to these improvements, the present study proposes the following developments which enhance REPAC's ability to simulate the impact of ZEV infrastructure provision on the ZEV market:

1. Enhanced resolution on ZEV infrastructure representation, differentiating among home, workplace, public destination, and DC fast charging access, along with the inclusion of hydrogen infrastructure

2. The estimation of updated (2017) Canada-wide consumer-preferences for ZEVs, including consumer valuations for each of the above infrastructure access types
3. Other updated inputs such as ZEV prices, dealership availability, vehicle variety and infrastructure access across Canadian provinces, (including the province of Quebec, which was previously not included in REPAC)
4. The inclusion of HFCVs as a competing drivetrain among previously modelled drivetrain types (CVs, HEVs, PHEVs, and BEVs)
5. Enhanced resolution on vehicle model variety through the introduction of a fifth body class (trucks) among previously included class sizes (compact cars, sedans, mid-SUVs, and full-SUVs/minivans).

These updates and additions allow for better insights into the present-day ZEV market and the role of infrastructure in ZEV transition.

Chapter 2. Methods

REPAC is an agent-based model (ABM) (which has also been previously referred to as a “constrained choice model” by its authors) (Wolinetz & Axsen, 2017) that simulates new ZEV market share over time. It functions as a choice model, while accounting for additional barriers to ZEV adoption. Each agent represents an actual new-vehicle buying household in Canada in terms of their preferences, residential locale, and other aspects of their ZEV purchasing context based on data collected in a nationwide 2017 survey. This methods section describes 1) the collection of consumer data as inputs to the REPAC model, 2) the structure of the REPAC model and its sub-models, 3) my sensitivity analysis, and 4) the modelled scenarios.

2.1. Data Collection

The consumer-specific data for this study were collected via the Canadian Zero Emission Vehicles Survey (CZEVS 2017), which was administered by Simon Fraser University’s Sustainable Transportation Action Research Team (START) between January and April of 2017. It was largely replicative of its predecessor, the Canadian Plug-in Electric Vehicle Survey (CPEVS), implemented in 2013. The target population was new vehicle buyers across all of Canada which was defined as households who plan to purchase a new vehicle within the next 12 months. START recruited a representative sample of 2,124 new vehicle buying households identified with the help of a market research company, Research Now. 1,884 respondents are used in my current version of the REPAC model (omitting those who did not provide their gender, income, and other personal demographic information). The survey was framed as a ‘‘household vehicle survey’’ and only household (non-fleet) new vehicle buyers were contacted for this analysis.

The survey followed a two-part, “reflexive participant” approach intended to give respondents time to build familiarity with and develop preferences for ZEVs. Reflexive survey design can help improve behavioural realism in SP research methods by encouraging respondents to become familiar with the options in the survey, and to reflect on their own lifestyles and situations before submitting their responses. The CZEVS encouraged respondents to understand the different ZEV technologies, recharging and refuelling requirements, their own travel patterns, personal ZEV infrastructure access (at home, work, and other common destinations), thereby facilitating reflection upon whether or not a ZEV is compatible with their lifestyle.

Part 1 elicited details about respondents' intended next vehicle (make, model, body class – if known). It also assessed variables such as awareness of ZEV technologies and types, access to ZEV recharging/refuelling infrastructure at home and at work. It also collected the household's socio-demographic information. REPAC used the following data elicited from Part 1 to inform the 2017 (base-year) assumptions regarding respondent specific variables:

- Respondents' geographic location by city/town and province
- Self-reported familiarity with each ZEV drivetrain on a scale of 1-4, where 1=not familiar, 2=somewhat familiar, 3=moderately familiar, and 4=very familiar
- Approximate monthly driving distance in km (converted to a weekly average)
- Access to Level 1 charging (or better) at home, (as defined to be a regular 120V outlet within 25ft of where the respondent usually parks)
- Access to workplace (or school) charging (as defined as having more or more parking spots in proximity to a Level 1 outlet or a nearby charging station)
- Intended vehicle class and purchase price of next vehicle purchase

Following a minimum waiting period of at least 24 hours, respondents were presented with Part 2 of the survey, which elicited specific information about their ZEV preferences. Part 2 first informed respondents about ZEV terminology using a detailed Buyers' Guide describing the differences and similarities among conventional vehicles (CVs), hybrid vehicles (HEVs), to plug-in hybrids (PHEVs), battery electric vehicles (BEVs), and hydrogen fuel cell vehicles (HFCVs). Respondents then completed a design game, which allowed them to explore attributes among drivetrains and develop their awareness of ZEVs. Finally, respondents completed a stated choice experiment which allowed for detailed quantification of their preferences for vehicle attributes and charging infrastructure.

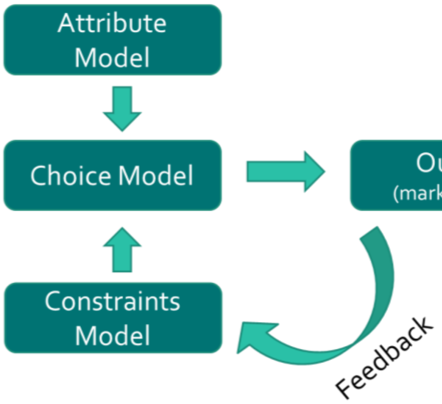
The 15 attributes included in this discrete choice experiment were: Drivetrain type (among CVs, HEVs, PHEVs, BEVs, HFCVs), purchase price (in CAD$), fuel cost ($/week), purchase incentive (CAD$), PHEV range (km), BEV range (km), HFCV range (km), home charging access (Level 1 or 2), work charging access (Level 1 or 2), destination charging access (% of destinations), DC fast charging access (as a network along major highways), and hydrogen refuelling access (% of gas stations). Thus, preferences could be calculated for each of these quantities, as further described in Section 2.2.1.

Other data were collected from various sources to update parameters in the model, such as an updated list of certified PEV dealerships, provincial fuel prices for gasoline, electricity, and hydrogen gas, provincial ZEV subsidies for each drivetrain type, the incremental purchase price of all ZEV drivetrains for each of the 5 vehicle classes, as well as available and announced ZEV models in Canada. Estimates were made to approximate Level 2 charging access in public locations, DC fast charging access, and hydrogen refuelling stations across Canadian cities. The values used to populate these attributes in the model are described in Section 2.2.2).

2.2. REPAC Model

The REPAC model calculates new ZEV market share using three sub-models – an attribute sub-model, a choice sub-model, and a constraints sub-model (Figure 1). The attribute sub-model sets the attribute levels and characteristics of the vehicle options competing in the market. Based on these values, the choice sub-model determines each respondent’s preferred vehicle choice and sums these to estimate the size of the latent ZEV market. As described previously, latent demand is greater than realized market demand (also referred to as constrained market demand) for ZEVs because it describes the ZEV market in the absence of important contextual constraints. Thus, the constraints sub-model is applied to account for respondent-specific ZEV barriers that were not capture through the choice experiment, such as whether or not a respondent is familiar with ZEV vehicle options in the first place, has an abundance of ZEV models to choose from, or lives sufficiently close to a dealership that stocks and is authorized to sell ZEVs.

Imposing these constraints on choice model output can help avoid artificially high uptake estimates that neglect the purchasing contexts that consumers face. A feedback loop allows consumer familiarity to increase endogenously over time as ZEVs gain market share.)



Adapted from Axsen & Wolinetz (2017)

Figure 1. Respondent-based Preferences and Constraints (REPAC) Model

For the purposes of this study, the term “attribute” describes ZEV characteristics that are applied in the choice sub-model’s utility calculation and whose levels are reflected in the estimates of latent demand. The term “constraint” refers to ZEV adoption factors that are applied by the constraints sub-model and detract from latent demand. Colloquially, both attributes and constraints might be considered as ZEV adoption “barriers” depending on the levels at which they are specified. For example, the home charging attribute may be considered an adoption barrier by individuals who don’t have home recharging access. Similarly, some may consider a ZEV’s driving range to be an adoption barrier if it does not meet their daily driving needs (as represented by negative preferences for the ZEV). Constraints and attributes are listed in Table 2.

Because ZEV policies, infrastructure, and other attributes vary across Canada, the model is disaggregated to capture differing ZEV conditions in the following provincial groupings: British Columbia, Ontario, Quebec, and the rest of Canada. (The Territories are omitted from my analysis as no survey data was collected for the Territories.) ZEV respondents are subject to the conditions specified within the provincial grouping of their residence. New market share is calculated for each provincial grouping then combined to form Canada-wide output. The reported results are weighted based on 2016 census data[3] to correct for oversamples from certain provinces in the CZEVS survey. (A description of the sample, as compared to Canadian census, is included in Appendix A.)

Table 2. Model Attributes and Constraints

Attributes: (modelled by the choice sub-model)	**Constraints:** (modelled by the constraints sub-model)
• Purchase price • Weekly fuel costs • Financial incentive (i.e. purchase subsidy) • Driving range • Home charging access • Workplace charging access • Destinations charging access • DC fast charging access • Hydrogen refuelling access	• Respondent familiarity • Availability at dealerships • Make and model variety

Because ZEV infrastructure access and infrastructure policies tend to differ in urban versus remote areas (Newman et al., 2014), I further include resolution that differentiates among urban, semi-urban, and rural region types within each provincial grouping based on population density from the 2016 Canadian census. I classify regions that fall within Census Metropolitan Areas (total population of at least 100,000) as urban, within Census Agglomerations (core population of at 10,000-50,000) as semi-urban, and any remaining regions I classify as rural. Where greater resolution is available, some data parameters apply at the city-level. For example, the distribution of certified ZEV dealerships and hydrogen refuelling station are represented by city.

2.2.1. Choice Sub-Model

Using the data from the choice experiment in Part 2 of the CZEVS, Axsen et al. (2017) estimated a latent class choice model using Latent Gold 5.0 to approximate vehicle preferences among Canadians. In latent class models (LCMs), respondents are grouped into various segments, or “classes” based on demographic, lifestyle, or

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[3] Where British Columbia accounts for 13% of Canadian population (and 24% of the sample), Ontario accounts for 39% of the Canadian population (and 39% of the sample), Quebec accounts for 23% of the Canadian population (and 15% of the sample), and the rest of Canada accounts for the residual 25% of the Canadian population (and 23% of the sample), based on 2016 Canadian census data (Statistics Canada, 2016).

attitudinal similarities, which reflect how their decision-making patterns differ from other segments of the population. Preferences are calculated for each individual class (instead of the sample as a whole) which can improve the fit of the choice model and allows consumer heterogeneity to be better represented (e.g. Brand, Cluzel, & Anable, 2017; Axsen, Bailey, & Castro, 2015; Hidrue et al., 2011). Axsen et al. (2017) selected a five class solution. Each survey respondent was assigned to the latent class for which they had the highest probability of belonging (as recorded by the LCM posterior probabilities). The coefficients and some associated willingness to pay[4] (WTP) values for different attributes are available in Table 3 using asterisks to represent confidence levels.

The LCM coefficients, specific to each latent grouping, are used as inputs in the REPAC model to predict how consumers within each class will respond to changing attributes. The class-specific results demonstrate substantial heterogeneity in respondents' valuation of ZEVs and their attributes. The vehicle-specific-constant (VSC) values, which represent respondents' underlying interest in each drivetrain relative to a CV, show that some consumer segments (e.g. the CV and HEV oriented classes) have strong negative valuation of ZEVs, while others (e.g. the PHEV oriented and PEV enthusiast classes) have positive valuation of PEVs at statistically significant levels. No classes positively value the HFCV drivetrain. Infrastructure preferences from the LCM vary with only the PHEV oriented class showing statistically significant valuation of home, DC fast charging, and hydrogen infrastructure access. No classes value the presence of workplace charging or public destination charging at the 90% confidence level. In this study I use non-significant coefficients, whether positive or negative, as model inputs, rather than equating them to zero. By using the coefficients produced by the LCM, I am assuming that they are a fair representation of current consumer preferences. However, it is possible that the lack of significance could indicate that some survey respondents were confused by the survey instrument or by the concept of ZEVs more generally.

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[4] Willingness to pay (WTP) values demonstrates a respondents' valuation of an additional unit of an attribute in monetary terms. It usually describes the maximum price at which a consumer would be willing to purchase an item.

Table 3. Latent Class Model Coefficients (Canada-wide sample, n=2,124)

Segment name	**CV-oriented**		**HEV-oriented**		**ZEV-neutral**		**PHEV-oriented**		**PEV-enthusiast**	
Percentage of respondents in segment	23%		21%		21%		22%		13%	
Vehicle specific constants (CV as base)										
HEV	-2.86	***	1.49	***	0.653	***	1.29	***	1.07	***
PHEV	-4.89	***	-1.44	***	-0.610	*	0.543	**	2.62	***
BEV	-8.96	***	-4.90	***	0.0531		-2.97	***	1.90	***
HFCV	-5.77		-8.36	***	-0.604		-7.74	***	-3.87	
Measure of preferences (coefficients)										
PP - Vehicle purchase price (CAD$)	-0.000153	***	-0.000295	***	-0.0000316	***	-0.000291	***	-0.0000121	***
PI - Purchase incentive value (CAD$)	0.000130	***	0.000131	***	0.0000792	***	0.000297	***	0.0000973	***
FC - Fuel cost (CAD$/week)	-0.000371		-0.0134	***	0.0000790		-0.0181	***	-0.000322	
VR_{PHEV} - PHEV range (km)	0.00144		-0.000993		0.00334		0.00283		0.000597	
VR_{BEV} - BEV range (km)	0.00595		0.00346		-0.00275	***	0.00286		0.000963	
VR_{HFCV} - HFCV range (log of km)	0.153		0863		0.136		1.05	**	0.570	
HA - Home charging (Level 1 or 2)	-0.121		-0.228		-0.0187		0.657	***	-0.0495	
WA - Workplace charging (Level 1 or 2)	-0.299		0.199		0.116		0.0388		0.195	
DA - Public charging (% of destinations)	0.0144		0.00525		0.00465		0.00196		0.00229	
DC - fast charging (network on major highways)	0.821		0.193		0.169		0.302	**	-0.248	
HG - H_2 station availability (% of gas stations)	0.0173		0.0191		0.00145		0.0151	**	0.0104	
Implied willingness-to-pay$_{a,b}$										
Valuation of vehicle type ($ CAD)										
HEV (all else held constant)	($18,639)	***	$5,042	***	$20,638	***	$4,422	***	$87,920	**
PHEV-60km (all else held constant)	($31,379)	***	($5,095)	***	($12,940)	*	$2,453	***	$218,884	***
+ home charging	($32,166)	***	($5,867)	***	($13,531)	**	$4,712	***	$214,803	***
+ DC fast charging	($26,019)	***	($4,441)	***	($7,589)		$3,493	***	$198,460	***
BEV-220km (all else held constant)	($49,964)	***	($14,016)	***	($17,458)	**	($8,050)	***	$174,217	***
+ home charging	($50,751)	***	($14,788)	***	($18,049)	**	($5,791)	***	$170,136	***
+ DC fast charging	($44,604)	***	($13,361)	***	($12,107)	*	($7,010)	***	$153,793	***
HFCV-500km (all else held constant)	($31,456)	***	($10,136)	***	$7,692	*	($4,259)	***	($26,632)	
10% gasoline stations	($30,330)	***	($9,489)	***	$8,152	**	($3,741)	***	($18,098)	
50% gasoline stations	($25,827)	***	($6,902)	***	$9,992	**	($1,667)	*	$16,039	
100% gasoline stations	($20,198)	**	($3,668)		$12,291		$924		$58,709	
Valuation of infrastructure attributes ($ CAD)										
Home charging (of Level 1 or 2)	($787)		($772)		($591)		$2,259	***	($4,082)	
Workplace charging (of Level 1 or 2)	-$1,951		$674		$3,659		$133		$16,093	
Public charging (per % of destinations)	$75		$18		$147		$7		$189	
DC fast charging (network on major highways)	$5,360		$655		$5,351		$1,040	***	($20,424)	
Hydrogen stations (per % of gasoline stations)	$113		$65		$46		$52	**	$853	

*significant at a 90% confidence level, **significant at a 95% confidence level, ***significant at a 99% confidence level. Adapted from Kormos et al., (2018).

The implied WTP and marginal WTP estimates for ZEV drivetrains and recharging/refueling infrastructure access are included in the bottom half of Table 3 (calculated by Kormos, et al., (2018)), WTP values are calculated for all coefficients with significance again denoted where appropriate. Here, WTP and marginal WTP values are intended to provide a relativistic measure for comparing respondent valuation of drivetrains and attributes rather than a literal interpretation of consumer valuation.

WTP is calculated for HEV, PHEV, BEV, and HFCV drivetrains along with the inclusion of recharging and refueling access for each class. As per Table 3, respondents in the PHEV-oriented class are willing to pay an additional CAD $2,453 (over the price of a CV) for a PHEV with a 60 km battery range. When the presence of a DC fast charging network added (and everything else held constant), those consumer's WTP increases to CAD $3,493. The difference between these values, CAD $1,040, is the marginal WTP value for DC fast charging network for respondents from the indicated latent class. Oddly, some consumers exhibit a negative marginal WTP for charging attributes.

The choice sub-model uses respondent-specific information (including latent class membership from the LCM) to determine each respondent's most likely vehicle choice. It operates by first determining each respondent's utility for all five drivetrain types based on the attributes levels that are specified, then comparing respondents' utility for each drivetrain type to gauge latent demand.

A respondent's utility is calculated for each drivetrain type to identify the relative desirability of each option based on its attributes, as indicated in Equation 1, where $U_{i,j,k,l,}$, is person *i*'s utility for vehicle drivetrain type *j* based on their assigned latent class, *l,* and their intended vehicle's body class *k*. Utility coefficients (with values as indicated in Table 3) are represented as upper-case variables, attributes are represented as lower-case variables, and subscripts are used to signify the factors upon which the attribute levels and utility coefficients are dependent:

$$U_{i,j,k,l} = VSC_{j,l} + (p_{j,k} * PP_l) + (i_{j,p} * PI_l) + (f_{i,j,k,p} * FC_l) + (r_j * VR_{j,l}) + (h_i * HA_{j,l}) + (w_i * WA_{j,l}) + (d_{p,s} * DA_{j,l}) + (c_{i,p,s} * DC_{j,l}) + (g_{i,m} * HG_{j,l}) \qquad \textbf{(1)}$$

Table 4. Table of Coefficients and Attributes for Equation 1

	Coefficients:		Attributes:
$VSC_{j,l}$	Vehicle specific constant		
PP_{l}	Purchase price coefficient	**$p_{j,k}$**	Purchase price
PI_{l}	Purchase incentive coefficient	**$i_{j,p}$**	Purchase incentive (i.e. subsidy)
FC_{l}	Fuel cost coefficient	**$f_{j,k,p}$**	Weekly fuel cost
$VR_{j,l}$	Vehicle range coefficient	**r_{j}**	Driving range and
$HA_{j,l}$	Home charging access coefficient	**h_{i}**	Home charging access
$WA_{j,l}$	Work charging access coefficient	**w_{i}**	Workplace charging access
$DA_{j,l}$	Destination access coefficient	**$d_{p,s}$**	Destination charging access
$DC_{j,l}$	DC fast charging access coefficient	**$c_{p,s}$**	DC fast charging access
$HG_{j,l}$	Hydrogen gas refueling access coefficient	**$g_{p,s}$**	Hydrogen gas refuelling access

Variables denoted as applied in Equation 1, with subscripts indicating dependent factors, where:
i = individual survey respondent
j = drivetrain type
k = vehicle class
l = latent class
p = provincial grouping
s = city

The respondent's probability of purchasing each respective vehicle option is calculated by Equation 2, and is understood to be that individual's personal latent demand (*PLD*) for each of the five respective drivetrain types (where a fixed drivetrain type is denoted as *J* and variable drivetrain type is *j*):

$$PLD_{i,J,k,l} = \frac{e^{U_{i,J,k,l}}}{\sum_{j} e^{U_{i,j,k,l}}} \qquad \textbf{(2)}$$

Vehicle choice is probabilistic for each respondent, represented as a ratio of the likelihood that the respondent chooses an indicated drivetrain over all others. Total latent demand ($LD_{i,j,k,l}$) for each drivetrain across the whole market is estimated as the sum of the probabilities of vehicle purchase for an indicated drivetrain across all respondents (corrected for regional population proportions) expressed in Equation 3:

$$LD_{i,J,k,l,p,s} = \sum_{i} PLD_{i,J,k,l,p,s} \qquad \textbf{(3)}$$

2.2.2. Attribute Sub-Model

The attribute sub-model populates the levels of all vehicle-specific and infrastructure related attributes (bullets in the first column of Table 4) that are considered by agents in the choice sub-model. It uses respondent-specific information to populate these levels for each agent, as informed through survey responses. In this subsection I first detail the assumptions that are used to compose the vehicle specific attribute levels (purchase price, purchase incentive, weekly fuel cost, and driving range) and follow with the same for infrastructure attributes (availability of home, work, destination, and DC fast charging, as well as availability of hydrogen refuelling).

The attribute sub-model uses a respondent's desired vehicle class (compact, sedan, mid-SUV, full-SUV/minivan, or pick-up truck) to construct a CV, HEV, PHEV, BEV, and HFCV version of their intended next vehicle. For the purposes of REPAC, I assume that the simulated respondents only consider vehicle drivetrains within their desired vehicle class, which is supported by previous market research by Long (2018). Based on the vehicle class and drivetrain combinations, the sub-model determines the appropriate attribute levels, such as the purchase price of each competing vehicle option, its driving range, etc.

Purchase price assumptions for the initial simulation year (2017) were made to reflect the 2017 incremental purchase price for each drivetrain type relative to a comparable CV. Incremental prices are specific to each body class, as summarized in Table 5. While there is a great deal of variation in purchase prices among vehicles of the same body class, these values were chosen as averages that reflected the incremental purchase price of ZEV technologies in 2017 (Wolfram & Lutsey, 2016). For vehicle classes that currently do not offer ZEVs, extrapolations were made based on vehicle weight and the cost of batteries and/or fuel cell technology.

Table 5. Incremental Purchase Prices by Drivetrain and Body Class (over a comparable conventional gasoline-powered vehicle) in 2017

	Compact	Sedan	Mid-SUV	Full-SUV/minivan	Truck
HEV	$ 1,400	$ 1,700	$ 2,100	$ 2,500	$ 3,000
PHEV	$ 4,000	$ 4,800	$ 5,900	$ 6,900	$ 8,200
BEV	$ 15,000	$ 17,700	$ 23,400	$ 27,700	$ 32,900
HFCV	$ 25,400	$ 30,400	$ 38,300	$ 45,400	$ 53,800

In all simulations I applied a declining cost function based on technology cost trajectories reported by the International Council on Clean Transportation where the incremental purchase price of PHEVs decrease by 50% by 2030, BEVs decrease by

80%, HFCVs decrease by 80% (Wolfram & Lutsey, 2016). HEVs were excluded from the report but I chose a 25% reduction in purchase price by 2030 assuming marginal improvements for HEV batteries. Table 6 shows the incremental purchase prices of vehicle drivetrains in 2030.

Table 6. Incremental Purchase Prices by Drivetrain and Body Class (over a comparable conventional gasoline-powered vehicle) in 2030

	Compact	Sedan	Mid-SUV	Full-SUV/minivan	Truck
HEV	$ 1,120	$ 1,360	$ 1,680	$ 2,000	$ 2,400
PHEV	$ 2,000	$ 2,400	$ 2,950	$ 3,450	$ 4,100
BEV	$ 4,500	$ 5,310	$ 7,020	$ 8,310	$ 9,870
HFCV	$ 7,620	$ 9,120	$ 11,490	$ 13,620	$ 16,140

Vehicle range is chosen as a single value for each drivetrain type, meant to be reflective of the average (electric or hydrogen powered) driving range for each ZEV type, where PHEVs are assumed to have an 80km electric range, BEVs, a 200km electric range, and HFCVs a 400km hydrogen powered range. Fuel and electricity consumption are specific to each drivetrain and body class pairing, as presented in Table 7, with energy prices in Table 8.

Table 7. Energy Consumption Assumptions by Drivetrain & Body class

	Compact	Sedan	Mid-SUV	Full-SUV/minivan	Truck
Gasoline (L/100km)					
CV	9.4	10.2	10.5	13.2	14.1
HEV	5.5	6.2	8.1	9.5	10.4
PHEV*	2.2	2.5	2.9	3.2	4.4
Electricity (kWh/100km)					
PHEV*	17.0	18.5	25.2	29.1	33.7
BEV	18.4	21.3	25.1	29.5	33.9
Hydrogen (kg/100km)					
HFCV	1.3	1.7	1.6	2.1	2.2

Values based off NRCan Fuel Consumption Guide, 2017

*PHEV assumes a mix of 70% battery electric driving and 30% conventional driving

While variation exists in terms of vehicle range and energy consumption within drivetrain types, values were chosen that were in the mid-range of current technologies in 2017 and were also compatible with the incremental purchase price estimates. For simplicity, I assume vehicle ranges and energy efficiency to be static in the model over time, with technological improvements instead being captured through falling vehicle prices rather than these parameters. I investigate how sensitive the REPAC model is to the range assumption as well as fuel costs in my sensitivity analysis.

Electricity and fuel prices are shown by provincial grouping in Table 8. Because of uncertainty in future oil market and potentially large (positive or negative) impact on energy prices, gasoline and electricity prices are assumed to remain static over the projection period (though with applicable carbon taxes applied based on the scenario). However, I investigate the electricity and fuel price assumptions in my sensitivity analysis. The price of hydrogen is assumed to decrease from $6/kg to $4/kg by 2030 as hydrogen production gains economies of scale.

Table 8. Energy Prices by Province (2017)

	British Columbia	**Ontario**	**Quebec**	**Rest of Canada**
Gasoline ($/L)	$ 1.22	$ 1.13	$ 1.20	$ 1.13
Electricity ($/kWh)	$ 0.09	$ 0.13	$ 0.08	$ 0.10
Hydrogen ($/kg)	$ 6.00	$ 6.00	$ 6.00	$ 6.00

Values based off NRCan Average Retail Prices for Regular Gasoline, 2017

Weekly fuel cost, $f_{j,j,k,\mathrm{p}}$, (in $/week) is calculated for each respondent as per Equation 4, where fuel consumption of gasoline and/or electricity, or hydrogen fuel depends upon the respondent's weekly driving distance, their desired vehicle's body class, and the drivetrain type:

$$f_{i,j,k,p} = x_i * \left(\left(y_{i,j,k,} * Y_p \right) + \left(q_{i,j,k} * Q_p \right) + \left(z_{i,j,k} * Z_p \right) \right) \quad \textbf{(4)} \ .$$

where driving distance, x_i, is measured in km/week; gasoline consumption, $y_{i,j,k}$, is measured in L/100km; electricity consumption, $q_{i,j,k}$, is in kWh/100km; hydrogen consumption, $z_{i,j,k}$, is measured in kg/100km; gasoline price, Y_p, is in ($/L); electricity price, Q_p, is in $/kWh, and hydrogen price, Z_p, is in $/kg. The fuel price of each fuel depends upon the provincial grouping in which the respondent resides.

Home and work charging access is specified based on the survey responses for each respondent. In the initial simulation year, home and work charging access is binary, meaning a respondent either has charging access at home or they do not. A respondent is considered to have home charging access if they report that they can park within 25ft of a Level 1 outlet (or better) and have specified in the survey that they would be willing to use it to charge a vehicle. (I use Level 1 charging access as the minimum requirement so as not to be unduly restrictive). The proportions of respondents who reported meeting this requirement in 2017 are summarized by provincial grouping in Table 9 alongside other charging and refuelling access estimates.

Table 9. Charging and Refuelling Access in Canada (2017)

	British Columbia	Ontario	Quebec	Rest of Canada	Canada*
Level 1 home charging or better (% of respondents)	56%	56%	55%	65%	58%
Level 2 Home charging (% of respondents)	14%	16%	13%	13%	14%
Level 1 workplace charging or better (% of respondents)	38%	42%	27%	36%	36%
Level 2 workplace charging station (% of respondents)	16%	13%	14%	12%	13%
Level 2 at urban destinations (% of destinations)	2.5%	1.1%	2.2%	0.4%	1.4%
Level 2 at semi-urban destinations (% of destinations)	3.0%	1.9%	3.3%	1.1%	2.2%
Level 2 at rural destinations (% of destinations)	6.6%	0.0%	1.0%	0.4%	1.2%
DC fast charging networks on highways (on/off)	Off	Off	Off	Off	Off
Hydrogen refuelling (% of gas stations)	0%	0%	0%	0%	0%

*weighted average, all provinces
Level 1 or better refers to access to Level 1 and/or Level 2 charging

A respondent is considered to have workplace charging access if they report at least one parking spot in proximity to a Level 1 outlet or charging station at their place or work or study. Because workplace charging estimates appear higher than expected, it is possible that respondents may have overreported their potential to charge a vehicle at their workplace or school. Alternatively, some colder regions of Canada's do commonly have workplace access to "block heaters" which may explain a large portion of these reported outlets. To understand the implications of this potential bias on the model's results, I investigate how a decrease in the reported workplace charging assumption though my sensitivity analysis (described further in Section 2.5). In Table 9, I also report home and workplace charging access to Level 2 charging capacity in 2017 though I do not use these values in the current simulations.

Like home and work charging access, DC fast charging access is also represented as binary in REPAC. Instead of being informed by survey responses, DC fast charging availability has been estimated through online searches using Canada wide data (ChargeHub, 2017). Natural Resources Canada (2018a) estimates that only 490 DC fast charging stations are available across Canada in 2018 and most are highly concentrated within provinces. For this reason, I assume that DC fast charging networks across Canada are “off” in 2017 rather than “on” – that is, there is no current DC fast charging network in Canada. Admittedly, this is a simplistic way of representing DC fast charging.

Destination charging access is represented as a percentage of a respondent’s non-home, non-work destinations having Level 2 PEV charging capability. I estimated this value for an urban, semi-urban, and rural region type within each provincial grouping. To do this, I first used Canadian driving diary data (previously collected by Axsen, Bailey, and Kamiya, 2013) to estimate the percent of drivers’ destinations that reportedly had charging access across various Canadian cities in 2013. Then, using 2013 charger abundance data (Fraser Basin Council, 2017) and population density data (Statistics Canada, 2013) in these same cities, I determined a ratio between chargers-per-capita and percent of destinations having charging access. Using this ratio, as well as charging point (ChargeHub, 2017) and recent census population density (Statistics Canada, 2016), I was able to extrapolate the percentage of destinations in cities that had public chargers in 2017. Within each provincial grouping, I took the average value of all the urban cities to create a single urban-city public charging estimate, which I applied to all respondents in that spatial segment. The same was done for semi-urban, and rural region types for each provincial grouping.

Hydrogen refuelling is represented as a percentage of gas stations, captured at the city level. In 2017, there were no publicly accessible hydrogen refuelling stations in operation in Canada, but hydrogen gas was available at 3 private (non-retail) distributors or university research centres; one in Surrey, British Columbia; Mississauga, Ontario;

and Trois-Rivières, Quebec. These stations are captured in the model though at the provincial scale (displayed in Table 9) they are shown to round to zero.

2.2.3. Constraints Sub-model

The constraints sub-model imposes ZEV adoption constraints, specific to each respondent, that aren't accounted for as preferences in the calculation of utility. The three constraints I model are ZEV familiarity, dealership access, and vehicle model variety. These are modelled as constraints rather than attributes as they are inherently difficult to assess via a stated choice experiment. Familiarity is incompatible with a choice experiment because it can not be easily manipulated as part of a choice set, and a respondent must first be familiar with the options in order to choose among them. Dealership access and ZEV stock are functional barriers, rather than preferences, so they can not be specified in a choice experiment either. (However, future research could use choice experiments to assess how consumers value attributes associated with ZEV dealership access and stock, such as the ability to test drive a vehicle before purchasing, having to order their vehicle online, and/or the wait times associated with purchasing an out-of-stock ZEV). Vehicle variety could potentially have been included in a choice experiment, though would be difficult to contextualize in a way that would elicit meaningful results. The constraints are applied to utility as multipliers which reduce individuals' personal probability of ZEV purchase. Constraints can take a value ranging from zero to one, with zero corresponding to a total constraint (i.e. completely preventing a respondent from purchasing a ZEV) and one corresponding to total alleviation of that constraint.

In the base year (2017), the ZEV familiarity constraint is binary. The value is assigned based on each respondent's self-reported familiarity with each drivetrain type, as collected in Part 1 of the CZEVS survey (i.e. before reading the ZEV Buyer's Guide and before completing the design game or choice experiment). On a scale with the options of "not at all familiar", "somewhat familiar", "moderately familiar" and "very familiar" with an indicated ZEV drivetrain type, respondents must have rated themselves as at least "moderately familiar" in order to be assigned a "1" for this constraint. In each consecutive year, REPAC accounts for improved ZEV familiarity endogenously as a function of new ZEV market share. For each forecasted year, a respondent's familiarity with a given ZEV drivetrain can rise based on rising new market share from the previous year, enabling positive feedback. It is assumed that BEV and PHEV sales can improve familiarity across both PEV drivetrains, while HFCV familiarity is improved by HFCV sales only. Based on previous findings by Axsen, Mountain, and Jaccard (2009) the relationship is calibrated so that ZEV familiarity is unconstrained for all respondents when new market share of the appropriate drivetrain surpasses 10%. The ZEV familiarity constraint follows the logistic relationship in Equation 5:

$$ZF_{i,J,t} = \frac{1}{1+a*e^{-MS_{J,t-1}*b}} \tag{5}$$

where ZEV familiarity ($ZF_{i,J,t}$) in a given year, t, is a function of new market share of that drivetrain in the previous year; a is a constant that defines the shape of the curve (a=100); and b is a constant that defines the rate of change (b=75).

The second constraint, dealership access, describes how difficult or easy it is for consumers to locate and purchase a ZEV from a certified dealership. It is structured to account for two components: the abundance of certified ZEV dealerships in a region (as a ratio of ZEV certified dealerships to total dealerships) and ZEV stock (i.e. the availability of ZEVs on site to view, test-drive, and purchase). In order for a respondent to meet the dealership access criteria, they must reside within a two-hour drive of a city or town that has a certified ZEV dealership. Data to inform which cities and towns had certified PEV dealerships was obtained from the Canadian Automobile Dealers Association (courtesy of Navius Research) and supplemented through web searches. From this database, approximately 35% of dealerships in Canada were certified to sell ZEVs in 2017. The ZEV stock component of this constraint is applied to account for the additional barriers of not being able to test drive nor purchase a ZEV on site. In 2015, Bauman, Hacikyan, and Stevens (2015) found that any given PEV-certified dealership in Canada only had a 75% chance of having a PEV in stock to test drive or purchase, and those that did often only had one single vehicle. The limited stock makes it unlikely for a consumer to find their desired model and/or trim line for purchase. It is not possible to quantify the extent to which this lack of stock reduces ZEV purchase probability, but I assume a further 50% reduction in the dealership constraint value across all regions to account for the stock component in 2017. Notably, researchers have found ZEVs to be even further disadvantaged at the point of sale due to a lack of ZEV knowledge by sales personnel, their sharing of misinformation, dismissive attitudes, or lack of incentive to sell ZEVs (Johnson et al., 2016; Matthews et al., 2017; Zarazua de Rubens et al., 2018), though I do not quantify these effects for my analysis.

The final constraint, vehicle model variety, restricts consumers' probability of purchasing a ZEV based on how many different ZEV models exist in the market for their preferred body class. It is known that elements of vehicle variety (e.g. style, comfort, and brand) are important factors that influence vehicle selection (Choo & Mokhtarian, 2004) and a limited variety of ZEV models in the market reduces the likelihood that consumers will find a ZEV that suits their individual needs and preferences. The vehicle model variety constraint in REPAC follows a logistic relationship where a respondent's vehicle selection is fully constrained when zero models of an indicated drivetrain type are available in their desired body class, and becomes effectually unconstrained when vehicle model variety reaches 15 models in their desired drivetrain type and body class (across all brands). In 2017, 18 PHEVs, 11 BEVs, and zero HFCV models were available for sale on the Canadian market across all brands, inclusive of luxury vehicles (Plug 'N Drive, 2017). Of the PHEV models, nine were sedans, while only three BEVs were available as sedans. The vehicle model variety constraint, then, for a respondent interested in purchasing a sedan in 2017, would be 80% removed for PHEVs (i.e. reducing the respondent's probability of PHEV purchase by 20%), and 35% removed for BEVs (reducing their probability of BEV purchase by 65%). Vehicle variety is assumed to be equal across all of Canada and follows a business as usual trajectory and the extrapolation of current trends. The variety of available ZEV models is assumed to improve as new models (based on OEM announcements) enter the market in their anticipated year, with modest improvements in selection continuing after 2020 with partial attribution from Quebec's ZEV mandate.

Notably, the number of vehicle models required for ZEV variety to cease being a constraint is not empirically informed, and I test my assumption in my sensitivity analysis (see Section 2.6). Previous versions of REPAC have assumed vehicle variety to be unconstrained when six non-luxury models are available per vehicle class (Axsen & Wolinetz, 2018) (also lacking empirical basis). With the inclusion of luxury and high-end vehicles (above MSRP of $60,000) in my database, I raise this threshold to 15 vehicles per class as these models accounted for nearly half of Canadian ZEV options in 2017. I expect that my assumption is still conservative, noting that well over 50 models would be required in each body class to compete at the level of CV model availability in 2017 (Natural Resources Canada, 2018b).

The constraints sub-model applies the above three constraints to an individual's personal latent demand estimate to predict their real-world probability of following through with the purchase of each drivetrain type. The constrained personal demand calculation is expressed in Equation 6:

$$CPD_{i,j,k,s} = PLD_{i,j,k,l} * ZF_{i,j} * DA_{j,s} * MV_{j,k} \quad \textbf{(6)}$$

where $CPD_{i,j,k,s}$ is constrained personal demand for a respondent for an indicated drivetrain, j, $PLD_{i,j,k,l}$ is their previously assessed personal latent demand for that vehicle type, $ZF_{i,j}$ is the respondent's ZEV familiarity for the indicated drivetrain type, $DA_{j,s}$ is their dealership access constraint, and $MV_{j,k}$ is the vehicle model variety constraint.

Total constrained market demand, *CMD*, (i.e. the realized market demand) in number of vehicles for a particular drivetrain, is the sum of constrained personal demand for each drivetrain type across all individuals in the modelled ZEV market, expressed in Equation 7:

$$CMD_J = \sum_i CPD_{i,J,k,s} \qquad \textbf{(7)}$$

The new market share of each drivetrain (i.e. the proportion of sales for each drivetrain type) is calculated by dividing the market demand for a fixed drivetrain type by the total number of vehicles demanded across the market, as shown in Equation 8.

$$MS_J = \frac{CMD_J}{\sum_j CMD_j} \qquad \textbf{(8)}$$

All the collected data is used to populate the model in the base year (2017), then values change per year based on the modelled scenarios (described in the following section, 2.4). All model variables, aside from ZEV familiarity, are set based on exogenous assumptions. Notably, other relationships could have been endogenized in this model. For example, others have modelled ZEV dealership availability to endogenously respond to increased ZEV sales (e.g. Wolinetz & Axsen, 2017). However, due to a lack of an empirical basis for this relationship, I do not attempt to endogenize its effects. Similarly, some might assume that increasing ZEV sales might spur improvements in supporting infrastructure; however, since I am interested in testing the impact of infrastructure access on stimulating ZEV sales, I do not endogenize this relationship. Setting these assumptions exogenously allows me to better isolate and quantify their expected effects on new market share.

2.3. Model Scenarios

In alignment with my two research objectives, I use REPAC to simulate a total of eight scenarios, investigating the role of ZEV infrastructure in the policy landscape until the year 2030. The simulations are formulated as policy options which address various ZEV barriers through their implementation. The scenarios can broadly be categorized as following either a business as usual (BAU) policy trajectory, with current and announced Canadian policies in place, or a stringent policy portfolio trajectory (described further below). The eight scenarios are organized as follows and I describe each further in the following subsections:

Business as Usual Simulations:

- **BAU-static-infrastructure** – business as usual policies with 2017 infrastructure access held constant
- **BAU-reference –** business as usual policies (including current and announced infrastructure policies)

Infrastructure-Only Simulations:

- **BAU+ambitious-infrastructure –** business as usual policies with ambitious infrastructure policies
- **BAU+universal-infrastructure**– business as usual policies with universal infrastructure access by 2030

Stringent Policy Portfolio Simulations:

- **SPP-static-infrastructure –** stringent policy portfolio with 2017 infrastructure access held constant
- **SPP-reference** – stringent policy portfolio with baseline (BAU-reference) infrastructure access
- **SPP+ambitious-infrastructure –** stringent policy portfolio with ambitious infrastructure access
- **SPP+universal-infrastructure** – stringent policy portfolio with universal infrastructure access by 2030

2.3.1. BAU Scenarios

The set of BAU scenarios simulate ZEV uptake based on current technological trajectories and current and announced policies from 2017 to 2030 in Canada (though with BAU-static-infrastructure holding infrastructure constant at its 2017 availability). The BAU policies include:

- Canada's federal carbon price (which starts at $10 per tonne of CO_2 in 2018 and rises by $10 annually until reaching $50 per tonne in 2022),
- Provincial ZEV purchase incentives as they are offered per province, available until they run out (assumed to be available until the end of 2020) (See Table 10),
- Quebec's ZEV mandate (requiring that provincial ZEV sales in Quebec make up 15% of new vehicle market share by 2025), and
- Charging and refuelling infrastructure deployment and improvements to building codes (excluded in BAU-static-infrastructure)

ZEV purchase incentives, which vary across Canadian provinces, are typically dependent on drivetrain type and range characteristics as well. Because I use a single range option per drivetrain, only one subsidy value is modelled per province (see Table 10). Subsidy values for 2017 are based off provincial programs (the Clean Energy Vehicles for British Columbia program in British Columbia, the Electric and Hydrogen Vehicle Incentive Program in Ontario, and the Purchase or Lease Rebate Program in Quebec). It is uncertain how long these subsidies will remain available as the program duration is dependent on fund depletion rather than a fixed term length. As an approximation, I assume that subsidy programs conclude at the end of 2020.

Table 10. ZEV Subsidies by Province (2017 - 2020)

	British Columbia	Ontario	Quebec	Rest of Canada
PHEV (80 km range)	$ 2,500	$ 3,000	$ 4,000	$ 0
BEV (200 km range)	$ 5,000	$ 14,000	$ 8,000	$ 0
HFCV (400 km range)	$ 6,000	$ 14,000	$ 8,000	$ 0

Across the BAU policy scenarios, ZEV model variety is assumed to grow from 29 models to a total of 85 by 2030 as summarized in Table 11. With the 2030 variety of ZEV models available in the market, Canadian ZEV variety is 90% unconstrained for PHEVs, 78 unconstrained for BEVs, and 30% unconstrained for HFCVs. Dealership access and ZEV stock is assumed to improve with increasing sales. In the BAU scenarios, I assume that the dealership constraint improves by 40% for PEVs and 20% for HFCVs across all provinces except Quebec where both improve by 60% as OEMs certify more ZEV dealerships and improve stock to comply with the ZEV sales mandate. Because Quebec is the only province implementing a ZEV mandate in the BAU simulations, I assume provincial dealership access to be the only method of compliance taken by dealerships. The impact of improved ZEV demand in one province is likely insufficient to improve economies of scale such as to enable improvements in other ZEV supply characteristics such increased ZEV model variety.

Table 11. ZEV Model Variety – Number of Models in 2017 and 2030 (BAU)

	2017			2030		
	PHEV	**BEV**	**HFCV**	**PHEV**	**BEV**	**HFCV**
Compact	4	7	0	16	7	1
Sedan	9	3	0	12	13	3
Mid-SUV	2	0	0	11	6	3
Full-SUV/minivan	3	1	0	4	5	1
Truck	0	0	0	0	0	0
Total:	18	11	0	44	31	8
		29 ZEV models			85 ZEV models	

I summarize all infrastructure access assumptions for 2017 as well as 2030 (i.e. for all infrastructure policy scenarios) in Table 12. In BAU-static-infrastructure I assume that all ZEV infrastructure types stay constant at 2017 values until 2030. In BAU-reference, which follows a business as usual trajectory for all policies including infrastructure, I assume that home and workplace charging increases by 20% of its 2017 value in urban and semi-urban British Columbia, Ontario, and Quebec, where building codes, home installation rebates, and charging station deployment initiatives are in place to support increased charging access. I assume that destination charging access reaches 10% of public destinations in urban and semi-urban regions of these provinces as well, for the same reasons. By 2030, this means that 65% of respondents have home

Table 12. 2030 Infrastructure Access Assumptions by Scenario

	Constant access	BAU reference	Ambitious infrastructure	Universal infrastructure
British Columbia (13% of population)				
Level 1 home charging or better (% of respondents)	56%	65%	83%	100%
Level 1 workplace charging or better (% of respondents)	41%	53%	78%	100%
Level 2 destination charging* (% of destinations)	2.7%	10%	20%	100%
DC fast charging network access (% of respondents)	0%	96%	96%	100%
Hydrogen refuelling* (% of gas stations)	0%	1%	10%	100%
Ontario (39% of population)				
Level 1 home charging or better (% of respondents)	56%	64%	82%	100%
Level 1 workplace charging or better (% of respondents)	49%	60%	87%	100%
Level 2 destination charging* (% of destinations)	1.0%	10%	20%	100%
DC fast charging network access (% of respondents)	0%	88%	88%	100%
Hydrogen refuelling* (% of gas stations)	0%	1%	10%	100%
Quebec (23% of population)				
Level 1 home charging or better (% of respondents)	55%	63%	82%	100%
Level 1 workplace charging (% of respondents)	33%	47%	84%	100%
Level 2 destination charging* (% of destinations)	2.2%	10%	20%	100%
DC fast charging network access (% of respondents)	0%	85%	85%	100%
Hydrogen refuelling* (% of gas stations)	0%	1%	10%	100%
Rest of Canada (25% of population)				
Level 1 home charging or better (% of respondents)	65%	67%	72%	100%
Level 1 workplace charging or better (% of respondents)	42%	46%	87%	100%
Level 2 destination charging* (% of destinations)	0.5%	4%	20%	100%
DC fast charging network access (% of respondents)	0%	0%	88%	100%
Hydrogen refuelling* (% of gas stations)	0%	0%	10%	100%
Canada Overall (100% of population)				
Level 1 home charging or better (% of respondents)	58%	65%	80%	100%
Level 1 workplace charging or better (% of respondents)	43%	53%	85%	100%
Level 2 destination charging* (% of destinations)	1.4%	8.5%	20%	100%
DC fast charging network access (% of respondents)	0%	66%	88%	100%
Hydrogen refuelling* (% of gas stations)	0%	0%	10%	100%

*indicates the weighted average of charging or refuelling access across all urban, semi-urban, and rural region types

charging access, 53% have Level 1 workplace charging access, and almost 8.5% of destinations among Canadian drivers have Level 2 charging stations. DC fast charging access is switched from being fully “off” in 2017 to being “on” along urban and semi-urban highway networks in British Columbia, Ontario, and Quebec (while remaining off in the rest of Canada). This means that by 2030, 66% of Canadian respondents are assumed to reside in proximity to an expansive DC fast charging network. Hydrogen refueling access is assumed to reach 1% of gas stations in urban and semi-urban British Columbia, Ontario, and Quebec, equaling about 0.7% of gas stations as a Canadian average.

2.3.2. Infrastructure-only Policy Scenarios

The infrastructure-only scenarios follow the baseline projection for all inputs aside from infrastructure. The BAU+ambitious-infrastructure scenario is meant to simulate a BAU trajectory with ambitious (but potentially attainable) levels of infrastructure deployment. In this sub-scenario, infrastructure aggressively increases across all provinces and region types (urban, semi-urban and rural regions), meaning that by 2030, 80% of respondents have charging access at home (instead of 56% in 2017), and 85% have workplace charging (instead of 43% in 2017). Destination charging access reaches 20% of public destinations across Canada, DC fast charging access becoming available along all urban and semi-urban highway routes across all provinces, and hydrogen refuelling increasing to 10% of gas stations by 2030.

The BAU+universal-infrastructure scenario is simulated for illustrative purposes, meant to demonstrate the maximum potential ZEV market share growth from infrastructure provision. In this sub-scenario, ZEV infrastructure reaches universally available levels by 2030, meaning that 100% of respondents across Canada have access to home and work charging, Level 2 charging is available at 100% of their destinations, DC fast charging is available along all major highway routes, and one hydrogen refuelling station is available for every gas station present in 2017.

2.3.3. Stringent Policy Portfolio Scenarios

The stringent policy portfolio that I use in the following simulations is designed to include a collection of policies that achieve approximately 30% new ZEV market share, nationally, by the year 2030. The portfolio employs a combination of policies including a strengthened carbon tax, increased ZEV subsidies, and increased vehicle supply via a

Canada wide ZEV sales mandate. The carbon tax follows the BAU specifications but continues to rise by $10 per tonne of CO_2 after 2022, reaching $100 per tonne by 2027 then staying constant. A ZEV subsidy of $8,000 is applied to all ZEVs equally, in all provinces, until 2025, then decreases to $2,000, staying constant until 2030. The national ZEV mandate is structured to match that of Quebec, where ZEVs are required to make up 15% of vehicle sales by 2025. In compliance with the ZEV mandate, dealership access and stock are assumed to improve by 60% by 2030 (whereby 98% of respondents are unconstrained by 2030), simulating a response by OEMs where measures are taken to improve the abundance of certified dealerships and ZEV stock at those dealerships. As an additional means of compliances, OEMs are assumed to take proactive measures by increasing ZEV model variety (Wesseling et al., 2014) such that at least five additional vehicle models are available for each drivetrain and body type by 2030, reaching a total of 125 ZEV models on the market. This means that 84% of Canadians are estimated to be unconstrained by PEV model variety by 2030 and 63% are estimated to be unconstrained by HFCV variety, approximating a 50% increase in ZEV variety compared to the BAU scenarios. This approach to modeling the ZEV mandate is perhaps conservative in that it only assumes improvements in vehicle supply and does not consider other potential technological advancements that could result from increased production, such as price reductions or improved vehicle range (Axsen & Wolinetz, under review). Of note, the stringent policy portfolio was formulated to be technology neutral in that it delivers improvements to all ZEV technologies equally.

The stringent policy portfolio is applied across four sub-scenarios where infrastructure varies by the previously described infrastructure scenarios (i.e. 2017 infrastructure access held constant, BAU-reference infrastructure deployment trajectory, ambitious infrastructure trajectory, and universally available infrastructure access by 2030).

2.4. Sensitivity Analysis and Treatment of Uncertainty

I conducted a sensitivity analysis that investigates how the REPAC model responds to various uncertain input assumptions. A sensitivity analysis in modelling can help inform modellers which assumptions drive the largest (or smallest) changes in the output. In doing so, the researcher can help identify important caveats in results, and identify priorities for further research. I investigated the model's sensitivity to ten input parameters which are either uncertain by nature (e.g. future values), simplified for representation in the model (e.g. average-value assumptions or scores), are estimated based on dataless, non-empirical values (such as in the case of the familiarity rate-constant), or might reflect erroneously reported values (such as the abundance of workplace charging access). I rank the sensitivity of the parameters with respect to their impact on 2030 new market share, using the BAU-reference scenario as my base.

The ten parameters I test are: the vehicle variety scaling factor; the ZEV dealership stock scalar; the endogenous familiarity rate constant (b); the familiarity-rating threshold; the destination charging estimate; ZEV driving range for each drivetrain type; the 2030 fuel prices for gasoline, electricity, and hydrogen gas; and respondents' reported access to workplace charging. The first three are dataless and therefore the least certain as inputs. In the sensitivity analysis, I vary each parameter by a high and low value, typically +/-25% of the assumed 2030 value. Since the familiarity rating is not a numerical value, I test the effect of reclassifying the threshold value of familiarity by strengthening it by one increment (i.e. so as to restrict familiarity to apply only to respondents rating themselves as "very familiar", instead of including those who rate themselves as "moderately familiar"), and relaxing it by one increment (to include those who rate themselves as "somewhat familiar" with ZEVs in addition to "moderately familiar" and "very familiar"). In the case of workplace charging access, I test an extreme case where workplace charging is assumed to be completely unavailable. Testing this assumption allows me to determine the impact on new market share in a worst-case-scenario of workplace charging overreporting.

I use the spread of the results in my sensitivity analysis to inform the uncertainty ranges in my projections (described in more detail in Section 3.1). Since the uncertain parameters are mostly tied to constraints (which are multiplied together), I estimate the 2030 market share uncertainty ranges using the standard propagation of errors formula for multiplication (root sum of the squares), as shown in Equation 9:

$$\frac{u(ms)}{MS} = \sqrt{\left(\frac{u(a)}{A}\right)^2 + \left(\frac{u(b)}{B}\right)^2 + \left(\frac{u(d)}{D}\right)^2} \qquad \textbf{(9)}$$

where new ZEV market share in 2030 (MS) has an uncertainty range u(ms) determined by the uncertainty of the model availability scaling factor (A) which has an uncertainty range of ±u(a), the familiarity rate constant (B) with an uncertainty range of ±u(b), and the dealership stock scalar (D) with an uncertainty range of ±u(b).

Chapter 3. Results

To preface the results of my simulations, I begin this section with the results of my sensitivity analysis and description of the model's uncertainty. I then describe output from the base year of the model (i.e. 2017), which describes the current market conditions at the time the survey was taken. Following that, I present the results from each of the policy scenarios I simulated over the 13 year time span from 2017 to 2030.

3.1. Sensitivity Analysis

I tested nine of the uncertain input parameters in my sensitivity analysis to determine how the model responds to their uncertainty. As I describe later, the baseline (BAU-reference) market share projection produces a 2030 ZEV market share estimate of 9%. The sensitivity analysis shows how much higher and lower the market share projection could be if the indicated parameter is raised or lowered by the described amount. The results are displayed in Figure 2 with the most sensitive parameters at the top of the figure (descending order). Orange bars show market share deviations induced form decreasing the parameter values as indicated, and green bars show the market share deviations induced from increasing parameter values.

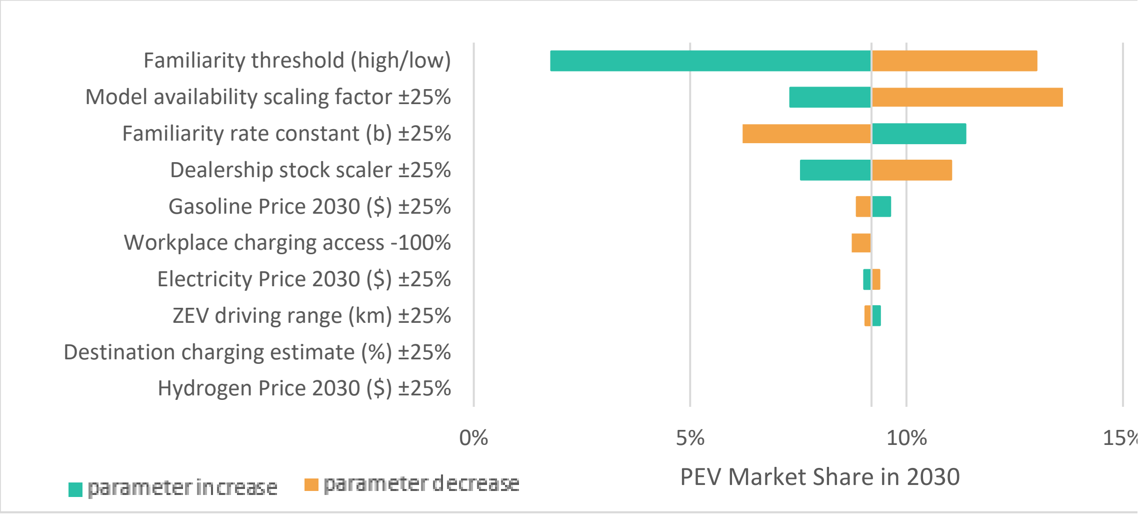

Figure 2. Sensitivity Analysis with Respect to 2030 BAU-reference Output

Of the parameters (and ranges) I investigated, the REPAC model is most sensitive to assumptions in the consumer familiarity rating threshold (i.e. the value at which a respondent is sufficiently familiar with a ZEV to overcome this purchasing constraint). By raising the threshold familiarity value by one increment (on a five-point scale), new ZEV market share in 2030 drops by seven percentage-points. Relaxing the threshold by one increment raises 2030 market share by four percentage points. REPAC is also sensitive to the model availability scaling factor assumption (i.e. the scaling factor that describes the number of vehicle models of the same body class and drivetrain type a consumer needs for unconstrained vehicle selection), which can impact the 2030 new ZEV market share estimate by +4/-2 percentage points.

The REPAC model shows little sensitivity to assumptions in gasoline, electricity, and hydrogen prices, with the price of hydrogen having a negligible impact on 2030 new ZEV market share in the BAU-reference scenario when varied by +/-25%. To supplement this, I also determined that neither a 100% increase nor decrease in the price of hydrogen fuel has a noticeable impact on 2030 new ZEV market share in the BAU-reference scenario. The same is true for the destination charging access estimate, where doubling or completely removing destination charging access has a negligible impact on 2030 ZEV sales.

The REPAC results are also fairly insensitive to the input assumptions regarding workplace changing access. This value was tested due to potential overreporting in survey respondent’s potential to charge a PEV at work. The sensitivity analysis shows that even if workplace charging access were completely unavailable to Canadians in 2017, the market share projection does not deviate substantially (less than one percentage point by 2030).

I use the variation in the three least certain (dataless) parameters to inform the uncertainty ranges in my 2030 new market share estimates. Using the standard propagation of errors, I determined that 2030 market share, MS, has an uncertainty range of +0.053 and -0.047, meaning new market share could be 5.3 percentage points higher or 4.7 percentage points lower than the simulated value of 9.2%. As a percentage, this corresponds with a range of values that could be up to 63% higher or 48% lower than the reported value. The upper and lower market share bounds are reported on simulation results in Sections 3.3 through 3.5.

3.2. Base Year Latent Demand and Constrained Market Demand

Based on consumer preferences, charging access, and other attribute levels for 2017, latent demand for ZEVs in that year was simulated to make up 24% of new vehicle market share. As shown in the top bar of Figure 3, latent PHEV demand makes up 17 percentage points of latent ZEV demand, followed by BEVs (5 percentage points), and HFCVs (2 percentage points). This hierarchy of drivetrain preferences is expected based on the LCM preference inputs.

With all constraints applied, the model simulates constrained market demand of ZEVs to account for only 0.7% of new vehicle purchases in 2017 with PHEVs making up 0.5 percentage points and PHEVs making up 0.2 percentage points. The new ZEV market share estimate is fairly consistent with observed sales for 2017 (approximately 0.9% market share (Klippenstein, 2018)), though with observed sales indicating equal proportions of BEV and PHEV uptake. The difference between the simulated values of ZEV latent demand (24%) and constrained market demand (0.7%) means that 97% of potential ZEV purchases did not translate into ZEV sales due to the presence of the three modelled constraints (elaborated on below). Because the impact of the constraints is so significant, it is worthwhile to note how each contributes to the constrained market demand estimate. In Figure 3 I show the impact that each individual constraint imposes on 2017 latent ZEV demand when applied at the levels in which they existed in Canada that year. Total 2017 latent ZEV demand (i.e. with no constraints applied) is shown as the top bar, followed by constrained market demand for ZEVs in subsequent rows once accounting for the presence of each constraint individually. Constraints are ordered from top to bottom in order of increasing impact on ZEV sales. The bottom bar shows total constrained market demand in 2017 with all constraints applied at their 2017 levels.

In 2017, the vehicle model variety constraint accounted for a 13 percentage point reduction in ZEV sales on its own, more than halving latent demand for ZEVs. Because there were so few HFCV models available in the Canadian market in 2017, the ZEV variety constraint alone would have accounted for 100% of lost HFCV sales, even without other constraints applied. The familiarity constraint was more restrictive on overall ZEV sales, accounting for 16 percentage points of lost sales when applied in isolation (a 67% reduction in the potential ZEV sales indicated by latent demand). The constraint most widely responsible for restricting ZEV sales was the dealership constraint, accounting for 19 percentage points of lost ZEV market share when applied on its own (i.e. a 79% reduction in ZEV sales). There is overlap in the effect of the constraints, as most consumers are constrained by more than one.

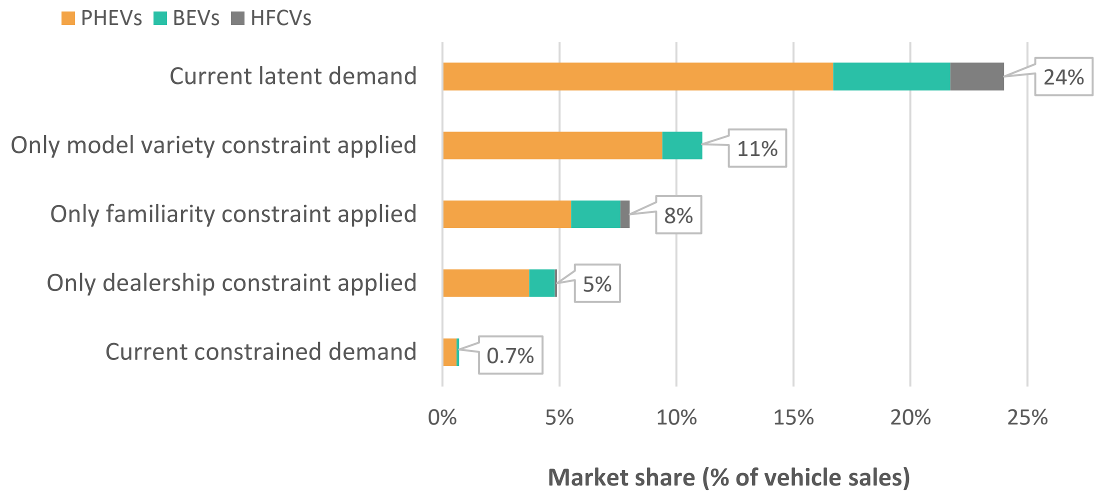

Figure 3. **New ZEV Market Share in 2017 with Constraints**

3.3. BAU Scenarios

As noted, new ZEV market share was simulated to be 0.7% in 2017. In BAU-static-infrastructure, as some constraints are lessened over time new market share reaches 7.6% by 2030, with a range of likely values falling between 3% and 13%. In the BAU-reference scenario, where infrastructure provision follows the trajectory expected from current and announced infrastructure policies, market share gains an additional 1.5 percentage points compared to the results in BAU-static-infrastructure, reaching 9.2% by 2030 (with a range of likely values falling between 4% and 14%). The BAU-reference projection is shown in Figure 4 (projected values only) alongside the same for all other simulations. The BAU-reference output is shown again but with its uncertainty ranges in Figure 5. Because of considerable overlap with uncertainty ranges applied among sub-scenarios, only the highest infrastructure simulations are displayed relative to BAU-reference in Figure 5. Thus, the four scenarios depicted in Figure 5 are:

1) BAU-reference (BAU with reference-case infrastructure levels)

2) BAU+universal-infrastructure

3) SPP-reference (stringent policy portfolio with reference-case infrastructure)

4) SPP+universal-infrastructure (stringent policy portfolio with universally available infrastructure)

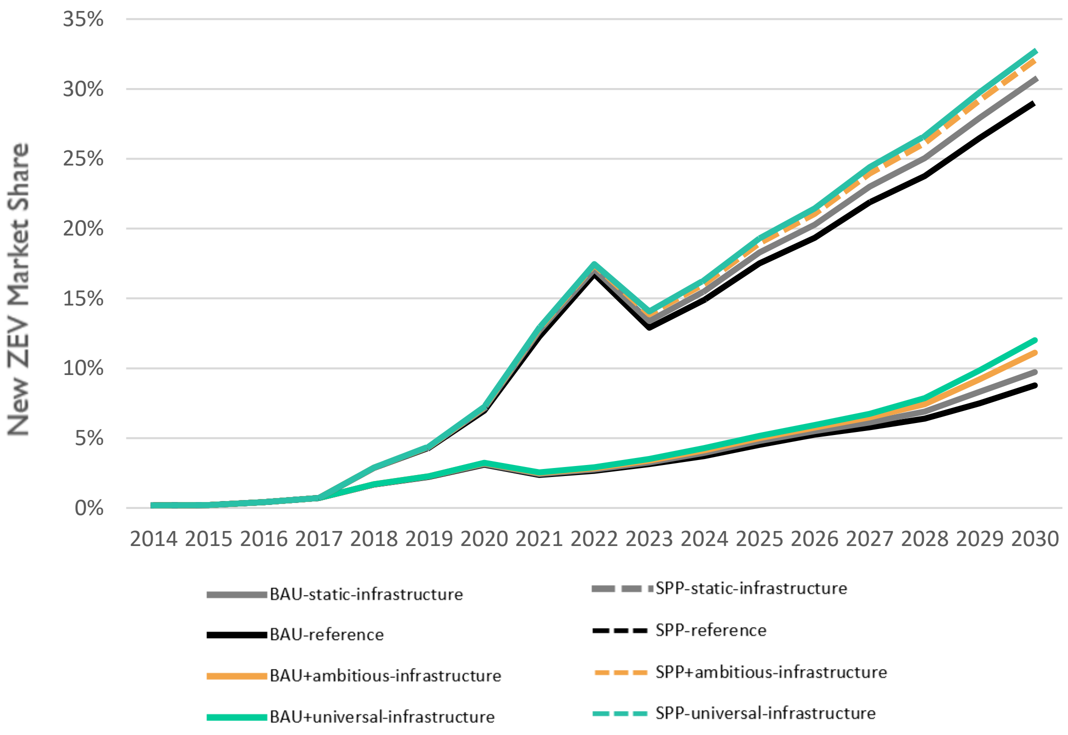

Figure 4. **Policy Dependent New ZEV Market Share Projections to 2030**

In BAU-reference, PHEVs make up the largest proportion of ZEVs capturing 6.5% of the market by 2030, with BEVs making up the other 2.5%. HFCVs do not contribute to new ZEV market share in 2030 as they are outcompeted by PEVs. The overall trajectory of the BAU scenarios follow a slow but upward climb in new market share, with only a slight dip in ZEV sales after the removal of purchase subsidies, assumed to be depleted by the end of 2020. Following that, as barriers continue to decrease over time, market share grows slowly and steadily.

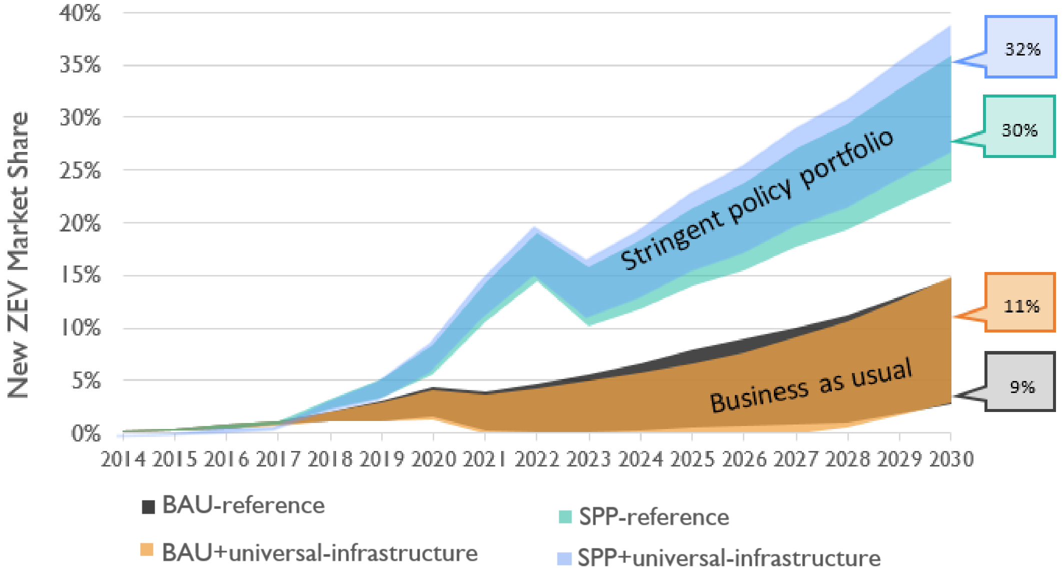

Figure 5. **Policy Dependent New ZEV Market Share Projections to 2030 with Uncertainity Ranges**

The projected 2030 new ZEV market share values are indicated on the far right hand side for each simulation.

3.4. Infrastructure-only Policy Scenarios

In the first infrastructure sub-scenario, BAU+ambitious-infrastructure where all ZEV infrastructure types are boosted to ambitious levels relative to BAU-reference, 2030 new ZEV market share is raised by less than one percentage point (0.8). The effect is broken down in Table 13 which shows the impact of each individual infrastructure type being raised in isolation, with their combined impact presented in the final row. The overall 0.8 percentage point growth in ZEV market share when all infrastructure attributes are increased simultaneously is attributed to an increase in BEV sales alone. PHEV and HFCVs sales remain unchanged. As per Figure 5, in the BAU+ambitious-infrastructure scenario, new market share of ZEVs in 2030 is 10% (with a range of likely values falling between 5% and 15%).

Table 13. Impact of Ambitious Infrastructure Deployment on 2030 Constrained Market Demand

Infrastructure type increased:	Infrastructure access in 2030:	2030 ZEV market share:	Δ 2030 ZEV market share
None (reference)	As specified in BAU-reference	9.2%	N/A
+ambitious home charging only	83% of respondents	9.6%	+0.4%
+ambitious workplace charging only	72% of respondents	9.4%	+0.2%
+ambitious destination charging only	60% of destinations	9.2%	+0.0%
+ambitious DC fast charging only	88% of respondents	9.3%	+0.1%
+ambitious H_2 refuelling stations only	10% of gas stations	9.2%	+0.0%
+ambitious all infrastructure types	(all the above)	10.0%	+0.8%

In BAU+universal-infrastructure, infrastructure is further boosted to reach universally available levels by 2030, meaning that 100% of respondents have access to home and work charging, access to Level 2 charging at 100% of their public destinations, DC fast charging access along all major highway routes across Canada, and hydrogen refuelling stations match gas station abundance. Again, the impact of raising each infrastructure type on its own is reported (see Table 14), with the combined impact in the final row. With all infrastructure types maximized, new ZEV market share in BAU+universal-infrastructure reaches 11% of vehicle sales in 2030 (8% PHEVs and 3% BEVs); only 1.5 percentage points higher than in the BAU-reference scenario. HFCVs are still unsuccessful at penetrating the vehicle market.

Table 14. Impact of Univerally Available Infrastructure on 2030 ZEV Sales

Infrastructure type increased:	Infrastructure access in 2030:	2030 ZEV market share:	Δ 2030 ZEV market share
None (reference)	As specified in BAU-reference	9.2%	N/A
+universal home charging only	100% of respondents	10.0%	+0.8%
+universal work charging only	100% of respondents	9.6%	+0.4%
+universal destination charging only	100% of destinations	9.2%	+0.0%
+universal DC fast charging only	100% of respondents	9.4%	+0.2%
+universal H_2 refuelling only	100% of gas stations	9.2%	+0.0%
All infrastructure types together	(all the above)	10.7%	+1.5%

3.5. Stringent Policy Portfolio Scenarios

In the stringent policy portfolio scenarios, a strengthened carbon tax, a ZEV sales mandate, and increased ZEV subsidies are simulated across Canada. The overall trajectory is much higher than the previously modelled simulations due to both an increase in latent ZEV demand (reaching approximately 40% in 2030) and significant alleviation of purchasing constraints, as described in Section 2.4.3. When stringent policies are in place, approximately 75% of latent demand can be unobstructed by constraints by 2030, compared to 30% in BAU-reference.

In SPP-static-infrastructure, where infrastructure is held constant at 2017 levels until 2030, new ZEV market share is simulated to reach 28.5%. In SPP-reference, when infrastructure is set to follow the BAU-reference case assumption, the model projects that 2030 ZEV market share reaches 30% by 2030 (with a range of likely values falling between 25-35%); about 21 percentage points higher than in BAU-reference. Market share initially peaks at 17% in 2022, dropping by five percentage points in the following year when the ZEV subsidy is decreased from $8,000 to $2,000. From there, market share takes a somewhat slower and more linear trajectory upward until 2030. In SPP-reference, PHEVs make up 24% of vehicle sales by 2030, BEVs make up 6%, and HFCVs still make up a negligible portion of ZEV market share.

In SPP+ambitious-infrastructure, when the stringent policy portfolio is supplemented with ambitious infrastructure implementation, the new market share projection rises very modestly, by a single percentage point, reaching 31% by 2030 (with a range between 26-36%). In this scenario, the single percentage point is attributed to an increase in BEV sales, which rise from 6.2% to 7.2% of the vehicle market. PHEV and HFCV sales remain constant at 24% and 0%, respectively.

In SPP+universal-infrastructure, when the stringent policy portfolio is modelled with infrastructure reaching universally available levels by 2030, new ZEV market share is forecasted to reach 32%, with the single percentage-point increase being attributed to PHEV sales. Notably, the alleviation of constraints to various degrees and the enhancement of other ZEV attributes in the stringent policy scenarios does not appear to enable any synergistic effects with the implementation of infrastructure. The incremental effect of infrastructure provision on market share remains constant and low (adding no more than two percentage points to total sales) regardless of what policies are in place to support ZEV adoption.

Chapter 4. Discussion and Conclusion

Transition from conventional vehicle use to that of ZEVs will positively contribute to Canada's climate action efforts. This study shows that the size of the ZEV market and its rate of growth is highly dependent upon the policies implemented to support ZEV technologies. Many barriers exist that currently prevent consumers from purchasing ZEVs. This study sought to quantify the potential market growth enabled by infrastructure provision, and to determine its capacity to support ZEV proliferation at the levels required to meet international GHG reduction targets (i.e. 30% new ZEV market share by 2030). Because representation of ZEV charging and refuelling infrastructure in previous analyses has been somewhat limited, this study sought specifically to capture resolution on home, workplace, public destination, and DC fast charging access, as well as hydrogen refuelling access across Canada. I use a behaviourally-realistic market forecasting model, with recently collected and empirically informed consumer preferences, to determine the extent to which ZEV infrastructure can increase Canadian ZEV sales. In the following sections, I summarize my results as they pertain to my research objectives, describe the policy implications from my findings, elaborate on the limitations of my study, and provide my concluding remarks.

4.1. The Role of Infrastructure Deployment in Stimulating ZEV sales

My first research objective sought to determine the extent to which ZEV infrastructure provision could boost ZEV sales across Canada. Consistent with findings by Harrison & Thiel (2017)and Silvia and Krause (2016), my results suggests that the role of infrastructure deployment in stimulating ZEV uptake is considerably limited. Under a business as usual trajectory, I have simulated that new ZEV market share will reach approximately 9% by 2030, with 1.5 percentage points being attributed to increased ZEV infrastructure. Additional infrastructure implementation beyond this level induces only minimal market share growth, even for very largescale deployment initiatives. When infrastructure is provided such that charging and refueling access is ubiquitously available to all Canadians by 2030, new ZEV market share is not expected to rise by more than 1.5 percentage points compared to the BAU-reference projection. In terms of the size of the present day market, this would correspond with an additional

30,000 ZEV sales. With the same maximization of home, work, and publicly acessible charging infrastructure in the U.S. (though omitting representation of DC fast charging and hydrogen refuelling infrastructure), Lin & Greene (2011) found a much more substantial 2,000,000 vehicle increase in annual U.S. ZEV sales by 2025, corresponding to a 12 percentage point increase in new market share. However, in both cases, fully gasoline powered vehicles continue to dominate the market (88-91% of sales) despite the complete removal of charging and refuelling constraints by the end of their projection (2025 and 2030, respectively). Overall, the contribution of ZEV sales from infrastructure provision does not significantly contribute to the IEA's proposed target of 30% new ZEV market by 2030.

There are two reasons that explain this underwhelming market response, with the first (and most prominent) being that consumer preferences for charging and refueling access, as collected through the CZEVS 2017, are considerably low. That is, ZEV infrastructure access does not seem to be a strong factor in the decision of whether or not an individual will purchase a ZEV. As cautioned previously, it is a limitation of this study that few of the LCM charging or refuelling preference coefficients were determined at a statistically significant level, though the values of the charging coefficients reflect similarities with previous research on Canadian home charging preferences where greater significance was observed (Axsen et al., 2015). Even where others have inferred higher WTP values for charging access (e.g. Brand et al., (2017) uses a WTP value of CAD $3,340 for daytime charging access in the United Kingdom, whereas destination and workplace charging produce an average WTP value of $1,904 among Canadians in the current study), stringent policies beyond infrastructure deployment were necessary to push ZEV sales beyond 30% new market share by 2030. Rather than charging access, respondents are consistently much more sensitive to financial attributes in vehicle purchasing decisions, such as purchase price (Gnann et al., 2015; Lin & Greene, 2011; Potoglou & Kanaroglou, 2007; Wolinetz & Axsen, 2017).

Secondly, there is the consequence of other existing constraints. While infrastructure provision (or other demand-side policies) may improve overall ZEV desirability to some degree, actual ZEV adoption may be obstructed due to limiting factors such as ZEV supply, or lack of ZEV awareness in the first place. Especially in the early years of ZEV adoption, the intended benefits of infrastructure provision (or other demand-focused policies generally) are suppressed due to the pervasiveness of these constraints. For example, the limited availability of certified ZEV dealerships, compounded by the problem of low ZEV stock at those dealerships, appears to be the most widely applicable barrier to Canadians who indicated interest in purchasing a ZEV in 2017. Eighty percent of the 2017 latent vehicle market would have been inhibited from ZEV purchase due to this constraint alone. Limited ZEV variety is another substantial constraint on the supply side which is thought to have prevented 54% of potential 2017 ZEV sales. Half of Canadian respondents from the CZEVS indicated that they intend to be purchasing a mid to large sized vehicle (mid-SUVs class or larger), yet 80% of available ZEVs models are offered in compact or sedan body classes. The HFCV drivetrain type is particularly supply constrained in Canada, with no models available for sale in 2017. A single HFCV SUV is expected to arrive in Canadian markets in 2018, which will still constrain a large proportion of the (albeit small) potential HFCV market. Even with BEVs and PHEVs, greater selection is needed both within and across body classes in order to ensure sufficient ZEV selection for consumers. Often, studies that have reported optimistic projections of ZEV market share have neglected to account for such constraints (e.g. Shafiei et al., 2012; Tran et al., 2013).

Overall, my REPAC simulations show that, without policies incremental to the business as usual policy projection, constraints are expected to remain considerable until 2030, at which point it is still expected to suppress 70% of the latent ZEV market.

My second research objective was to investigate what policies could be implemented to enable 30% new ZEV market share by 2030 – a ZEV adoption benchmark expected to enable deep greenhouse gas reductions in line with international climate mitigation targets (International Energy Agency, 2016). The policies I included in my simulated policy portfolio (necessary at stringent levels) were a strengthened carbon tax, increased ZEV subsidies, and a ZEV sales mandate. Together, these policies help address significant barriers of high upfront purchase prices and limited ZEV supply. This combination of stringent policies is shown to achieve 28.5% new ZEV market share by 2030 (a 20 percentage-point increase from the business as usual simulation), even when ZEV charging and refuelling infrastructure is assumed to remain constant at 2017 levels. When business as usual infrastructure deployment is simulated, 30% new market share can be achieved.

In my analysis, the simulated improvements in ZEV charging and refuelling access show the same impact on ZEV sales regardless of what other policies are in place to support ZEV sales. For example, upgrading infrastructure provision from the reference assumption to universal infrastructure access by 2030 improves 2030 ZEV market share by approximately 1.5 percentage points in both the business as usual and stringent policy projections. Conversely, Lin & Greene (2011) find the impact of improved recharge availability to be amplified when reductions in battery costs are applied.

While my analysis suggests that large increases in new ZEV market share can be realized through the implementation of very few policies, I do not further investigate an optimized approach. Policy optimization may be an interesting area for further research; however, a suite of policies is likely to be a politically favorable approach for stimulating the ZEV market as it will better ensure that barriers are alleviated across various consumer groups and demographics.

4.2. Policy Implications

The results of this analysis suggest that, without the intervention of strategically designed policies, new ZEV market share is likely to remain below 9% by the year 2030, and infrastructure deployment is not an important component of the policy portfolio that will help Canada contribute meaningfully to international climate targets. Noting that the effect is admittedly small, this study confirms that homes are likely the best priority for infrastructure provision among workplaces, public destinations, and highway charging locations, given the goal of encouraging ZEV adoption. Workplace charging access is second, followed by DC fast charging access along highways, then Level 2 charging at public destinations. As per the literature reviewed in Section 1, this general hierarchy is already widely supported through studies of various kinds (e.g. Bailey et al., 2015; Figenbaum & Kolbenstvedt, 2016; Hardman et al., 2018; Idaho National Laboratory, 2016), though with few studies including representation of DC fast charging. Hydrogen refuelling infrastructure was found to be the least effective infrastructure type for stimulating overall ZEV sales. While it would be a necessary factor in the success of widespread HFCV use, the implementation of hydrogen refuelling stations would not, in itself, be sufficient to stimulate HFCV adoption. Because consumer interest in HFCV adoption is small to begin with (less than 3 percentage points of latent ZEV demand by 2030), even substantial efforts directed at reducing HFCV barriers would only result in minimal increases in ZEV uptake. Continued competition from PEVs, which are currently more affordable, more familiar, and more available in the Canadian vehicle market, is likely to be an inhibiting factor in the market acceptance of HFCVs.

In the interest of maximizing ZEV market share growth from ZEV charging and refuelling infrastructure programming in Canada, (which currently tends to be directed at improving public charging access), this study suggests that greater attention should be given to measures that improve home charging access.

Notably, the minimal impact of other infrastructure types on ZEV sales does not necessarily mean that such policy measures should not be undertaken, as such improvements (while not appearing to be a deciding factor in ZEV uptake), may have other benefits. For example, previous researches have noted increases in electric kilometers travelled through the provision of PEV charging infrastructure (Funke & Plötz, 2017; Hardman et al., 2018) creating associated reductions in GHG emissions. However, as an attempt to stimulate ZEV sales in early years of market development, policy effort could be better spent in other areas.

Vehicle supply emerges as an important opportunity for policy intervention in the interest of climate action. Issues of ZEV supply can be combatted with policies that encourage manufacturers to produce, market, and sell ZEV models, such as has been done in select U.S. states, under a ZEV sales mandate. Policies that encourage ZEV sales (or penalize firms that do not comply) can help combat barriers of low stock, insufficient dealership certification, and limited vehicle variety. Additionally, through increasing sales, the ZEV mandate can accelerate consumer familiarity which was found to be a substantial barrier in early years investigated in study.

4.3. Limitations and Directions for Future Research

REPAC, as with all ZEV forecasting models, provides a simplified representation of real world exchanges, and results should be interpreted with full recognition of the model’s uncertainties and structural limitations. While the present adaptation contributes to the growing body of ZEV adoption modelling literature, there are important caveats to note and areas that can be improved upon in future research.

A large caveat with the REPAC method arises from the assumption upon which the model is calibrated. Latent demand is assumed to reflect the true unconstrained market demand for ZEVs, and the model's constraints are adjusted to make up the difference between latent demand and revealed market sales. While great care was taken to quantify the ZEV constraints at a level reflective of their current existence, remaining uncertainty in some parameters increase the possibility of error. Three dataless parameters (i.e. those that are not empirically informed) which exist in the REPAC model are:

1. The endogenous rate of familiarity increase (i.e. the rate at which familiarity grows as a function of new ZEV market share, which also describes the level of market share required to ensure that ZEV familiarity is fully saturated)
2. The ZEV model variety scalar, which describes the degree to which ZEV model variety limits or enables consumer uptake.
3. The portion of the dealership stock scalar that accounts for the degree to which purchase likelihood is constrained by the on-site unavailability of a consumer's desired vehicle model and/or trim.

Future research could be conducted to help inform dataless parameters.

Further, because latent demand is unrealized by nature, this estimate cannot be verified. Despite attempts to familiarize survey respondents with ZEV technologies and ground their responses in the context of their own situations, some degree of bias may persist. For example, because of the lack of consequence to their survey responses, and even the explicit suggestibility of ZEVs as an option in the survey's choice sets, respondents may have overrepresented their tendency for ZEV selection.

Another potential caveat in this study is that respondents have unlikely had sufficient exposure to ZEVs and their attributes to develop fully formed preferences for the vehicles, and especially for their charging infrastructure. Most mainstream consumers have not encountered real experience with charging a vehicle or using a hydrogen refuelling station, and so they might not yet know how to evaluate these when making trade-offs. Without full understanding of these attributes, it is possible that consumers may have underreported (or over-reported) the importance of charging or refuelling access in the survey. However, it is possible that early ZEV adopters neither had considerable experience with or fully formed preferences for charging/refuelling infrastructure at the time of their ZEV purchase either. The reviewed literature does not report how charging and refuelling preferences may differ between mainstream vehicle buyers and those who are likely to have fully formed preferences (such as long time ZEV owners), though understanding these differences (or deciphering more statistically significant coefficients) could increase the confidence of the current results. With regards to data reliability, it should be noted that the CZEVS data was screened for quality when finalizing the survey sample and all respondents who did not meet the data quality standards removed from the sample. For example, if respondents took less than a reasonable minimum amount of time to complete Part 2 of the survey, their answers may have been flagged as poor quality data. Respondents were removed if they failed multiple quality criteria checks.

While the current version of REPAC makes some important improvements regarding the level of specificity at which charging and refuelling infrastructure is represented, certain assumptions remain over-simplified. In particular, DC fast charging access is binary (represented as “on” or “off”) and applied at a very aggregate level (along major highways). This limitation is imposed by the way DC charging access was originally presented in the CZEVZ stated choice experiment. It is inherently difficult to delineate what constitutes available or unavailable at such broad levels of representation. Future research should seek to dial in the level of specificity for DC fast charging access representation.

Another limitation of REPAC is that, while it accounts for increasing familiarity over time, the model does not account for the ways in which consumer preferences towards ZEVs might change over time. It is possible that, as ZEVs become more prevalent in societies, or as concern over environmentalism and climate change grows, the LCM coefficients among vehicle types could shift to favour ZEV drivetrains over CVs. Technological development can further induce shifts in ZEV preferences. While PHEVs are easily the ZEV of choice from the preferences elicited from the CZEVS, (potentially due to their similarities with conventional HEVs and/or their potential characterization as a conservative “middle” option), continual improvement in battery and fuel cell technology may improve consumer confidence in these drivetrains and BEVs or HFCVs may emerge as a new obvious favourite. Forecasting how consumer preferences may change is inherently a complex endeavour, though the modelling work of Wolf et al., (2015), which proposes a novel representation of social contagion, may be a promising start.

In the absence of reliable predictions of changing preferences, REPAC should at least be improved to account for changes in other technological attributes over time such as increased ZEV range, or increased vehicle efficiency. The presented version of REPAC lacks sufficient endogeneity to capture all the dynamic ways that the vehicle market may evolve. I limit my projection to the 13 year period between 2017 and 2030, as projecting demand over long time horizons introduces greater uncertainty. A 13 year time frame is suitable for the current analysis since it is long enough to discern trends arising from policy implementation, and short enough to keep error within 10% of estimated values (as estimated through my sensitivity analysis). It is also a time span that is often relevant to governments from a policymaking standpoint. However, better endogenization of important relationships may improve a model's ability to represent future market conditions.

Finally, it would be beneficial in future versions of REPAC to capture the total ZEV stock over time in addition to annual market share. While it was beyond the scope of the present study, total stock of ZEVs on the road, including considerations on vehicle turnover, would help account for the total GHG reductions expected from the transportation sector based within the various policy projections. Such resolution is important in the interest of informed climate policy.

4.4. Conclusion

This study contributes to the growing body of behaviourally-realistic ZEV uptake modelling, delivering policy-dependent ZEV market share projections with enhanced resolution on ZEV infrastructure. In this study, I developed and employed a version of Wolinetz and Axsen's REPAC model, using an updated (2017) data set of 1,884 Canadian respondents nationwide, to estimate the impact of ZEV infrastructure deployment on Canadian ZEV market share.

In line with my research objectives, this study has found that:

1) The total impact of home, work, destination, DC fast charging, and hydrogen refuelling infrastructure deployment, even at unrealistically high levels, is projected to have a very minimal impact on new ZEV market share by 2030, (increasing market share by no more than 2 percentage points relative to the reference business as usual projection).

2) The impact of infrastructure implementation on ZEV uptake is small compared to that of other policies that reduce the barriers of ZEV supply (including access and variety), consumer familiarity, and upfront purchase prices.

3) The presence of stringent policy (e.g. a federal ZEV sales mandate and/or Canada-wide ZEV subsidies) may be needed to push ZEV sales towards climate friendly levels of 30% new ZEV market share by 2030 (or higher).

While greater infrastructure provision is expected to increase the convenience of ZEV use and provide benefits for ZEV users, it is not found to be effective at stimulating the levels of ZEV adoption required to meaningfully support climate policy. My findings suggest that there is a strong need for carefully selected policy intervention in driving the transition towards cleaner transportation. In order to see ZEV adoption at a rate that aligns with international greenhouse gas mitigation targets, a suite of policies should be designed to alleviate a wide array of ZEV barriers, including high purchase prices, limited ZEV stock and ZEV variety.

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Appendix A.

Demographic data for CZEVS respondents and Canadian Census data.

	CZEVS Sample	Canadian Census[a]
Sample size	2,123	
Population size		33,476,688
Age (of person filling out the survey)		
15-34	24%	31%
35-44	18%	16%
45-54	21%	19%
55-64	22%	16%
65+	15%	18%
Household income (pre-tax)[b]		
<$40,000	16%	25%
$40,000-$59,999	19%	19%
$60,000-$89,000	25%	24%
$90,000-$124,999	22%	17%
$125,000+	19%	15%
Highest level of education completed (of person filling out the survey)[c]		
Other	18%	60%
College, CEGEP, or other non-university diploma	34%	22%
University degree (Bachelor)	30%	14%
Graduate or professional degree	18%	5%
Residence type		
Detached House	65%	62%
Attached House (e.g. townhouse, duplex, triplex, etc.)	12%	17%
Apartment	22%	20%
Mobile Home	1%	1%
Residence ownership		
Own	77%	69%
Rent	23%	31%
Number of people per household		
1	19%	28%
2	42%	34%
3	20%	16%
4	20%	23%

[a] 2011 Census data is used as the complete set of 2016 Census data are not available. Census data are from Statistics Canada: http://www12.statcan.gc.ca/census-recensement/2011/rt-td/index-eng.cfm.

[b] excluded are n = 216 respondents (10.2% of the sample) who did not report their income from these proportions.

[c] excluded are n = 20 respondents (0.9% of the sample) who did not report their education from these proportions.

Borrowed from Long, (2018)