Modelling greenhouse gas emissions from light duty vehicles

Investigating policy actions for reducing emissions in British Columbia, Canada

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Faculty of Industrial Engineering, Mechanical Engineering and Computer Science
University of Iceland
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30 ECTS thesis submitted in partial fulfillment of a *Magister Scientiarum* degree in Environment and Natural Resources

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Abstract

This thesis investigates the potential for electricity and bioethanol to reduce greenhouse gas (GHG) emissions from light duty vehicle travel in the Canadian province of British Columbia. The purpose is to provide input into policy development for fostering a transition to a lower carbon transportation system. Systems analysis was conducted on the light duty vehicle system to identify leverage points for potential policy intervention. In order to quantify the impacts of various policy actions, a computer model was built using the mathematical modelling software, STELLA®, that projects annual GHG emissions from light duty vehicles in British Columbia up to the year 2050. The model simulates the market penetration of electric vehicles, composition of the fuel-mix for conventional vehicles, fuel efficiency of vehicles, and annual travel demand. A business-as-usual scenario and several policy scenarios were modelled and the resulting annual GHG emissions compared. The most ambitious policy scenario reduced GHG emissions to 66% below 2007 levels in 2050—a 54% improvement over business-as-usual—with electric vehicles comprising 41% of the light duty vehicle stock, and bioethanol meeting 32% of the fuel demand from conventional vehicles. Based on the results of the simulations, several policy recommendations were developed, including mandated sales targets for electric vehicles and increased availability of high ethanol blends in filling stations. While the policy scenarios explored here offer significant reductions in GHG emissions from a business-as-usual scenario, further work is required to explore an outcome where light duty vehicle travel approaches carbon neutrality.

Útdráttur

Í þessari ritgerð eru möguleikar á notkun rafmagns- og lífetanóls (e. bioethanol) í bifreiðum kannaðar með tilliti til minnkaðrar losunar gróðurhúsalofttegunda í Bresku Kólimbíu í Kanada. Tilgangurinn er að veita innsýn til stefnumótunar sem leiða á til þróunar samgöngukerfa, með áherslu á léttar farþegabifreiðar sem losa lítinn koltvísýring. Kerfisgreining var notuð til að greina mismunandi stjórnvaldsaðgerðir og var líkan hannað sem metur árlega losun gróðurhúsalofttegunda frá bifreiðum í Bresku Kólimbíu. Líkanið sem byggði á forritinu STELLA®, metur árlegt markaðshlutfall mismunandi bifreiða, nýtni eldsneytis, eldsneytisnotkun og kolefnislosun sem og árlegan fjöldi bifreiða til ársins 2050.

Miðað við þær forsendur sem líkanið gerir ráð fyrir gefa niðurstöður til kynna að rafmagnsbílar gætu verið um 41% af öllum bifreiðum á markaði árið 2050, á meðan lífetanól gæti uppfyllt um 32% af allri eldsneytisnotkun hefðbundinna bifreiða. Samsvarandi losun gróðurhúsalofttegunda gæti minnkað um allt að 66% frá 2007 til 2050, sem er um 54% lægri en losun gróðurhúsalofttegunda vegna venjubundinnar þróunar. Til að stuðla að stærri markaðshlutdeild rafmagnsbifreiða er mælt með stjórnvaldsaðgerðum sem miða að því að tryggja úrval margvíslegra tegunda rafmagnsbifreiða um leið og þær koma á markað, að auka þekkingu neytandans á tækninni og lækka kaupverð hlutfallslega í samanburði við hefðbundnar bifreiðar. Til að hvetja til aukins magns etanóls í árlegri eldsneytisneyslu er mælt með að lágmarks innihald etanóls í blönduðu bensíni verði hækkað, hærra hlutfall nýrra bifreiða verði með fjölorku vélar og framboð af eldsneyti blönduðu af etanóli og bensíni á bensínstöðvum verði aukið. Þess að auki ætti að stefna að framleiðslu lífetanóls sem er unnið úr beðmi (e. cellulose) úr úrgangi frá skógrækt í Bresku Kólimbíu. Þrátt fyrir að greiningin sýnir að mismunandi stjórnvaldsaðgerðir leiða til minnkunar í losun gróðurhúsalofttegunda í samanburði við venjubundna þróun, þarf að rannsaka frekar þær aðstæður sem leitt geta til samgangna sem eru kolefnisjafnaðar að fullu.

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Joel M. Zushman
Reykjavík
17.5.2016

1 Introduction

Greenhouse gas (GHG) emissions, most prominently carbon dioxide (CO_2), from the burning of fossil fuels are one of the greatest issues facing our planet today. Historically, increased GHG emissions have been tied to economic progress—black clouds of CO_2 the flag of a booming society. However, we are now at the point where anthropogenic GHG emissions are placing unrealistic stress on Earth and all its inhabitants. In their fifth assessment report, the International Panel on Climate Change (IPCC) state overwhelming evidence that anthropogenic emissions are drastically changing our environment, and insist that strong action must be taken immediately to mitigate GHG emissions if we are to limit the risks to humans and the environment at large (IPCC, 2014). A change in trajectory, away from high-carbon economies and towards greener, more sustainable development, is necessary if we are to preserve our well-being and that of future generations.

In 2010, annual global GHG emissions totalled 49 billion tons of CO_2-equivalent—nearly double the emissions from 1970—and are still increasing (IPCC, 2014). The largest contribution of GHG emissions worldwide comes from the production of electricity and heat, contributing 25% of the total annual emissions in 2010, followed by agriculture forestry and other land use (24%), industry (21%), and transportation (14%), with other smaller sectors making up the remainder (IPCC, 2014).

Although transportation is not currently the greatest contributor, global GHG emissions from the transportation sector have doubled since 1970 and are increasing at a faster rate than any other energy-use sector (Sims et al., 2014). This is mainly attributed to significant increases in road vehicles and their use, which historically is strongly coupled to GDP growth and rising incomes (Kyle & Kim, 2011). As of 2013, transportation accounted for 64% of all annual oil use (IEA, 2015) —94% of transport energy demand being met by oil-based fuels (Sims et al., 2014). Worldwide, and especially in developing nations, increases in income can cause a shift away from lower-emission public transportation systems towards increased personal light duty vehicle use, intensifying the consumption of liquid fossil fuels and thus the impact of transportation on the environment (Kyle & Kim, 2011). With the expected increase in transportation energy demands, particularly on roads, a challenge emerges in developing transportation management systems that reduce the dependence on oil for mobility, and shift the transportation fuel market towards renewables and low carbon options.

1.1 British Columbia, Canada

In the Canadian province of British Columbia (BC), transportation related emissions account for almost 40% of the total provincial GHG emissions, with more than one-third of those coming from light-duty vehicles— amounting to 13% of the provincial total (BC Provincial Government, 2014). As almost all of British Columbia's electricity comes by way of hydroelectric generation and produces very few emissions (BC Ministry of Environment, 2014a), fossil fuels burned for the transport of people and goods are the single greatest contributing factor of GHG emissions in the province, and thus represent the greatest opportunity for emissions reduction.

In 2008 the BC Provincial Government instituted the Climate Action Plan; a set of climate policies with the overall goal of reducing provincial greenhouse gas emissions to 33% below 2007 levels by 2020, and 80% below 2007 levels by 2050 (BC Provincial Government, 2008). Policies geared towards emissions from road vehicle use include a carbon tax, renewable and low carbon fuel standard, and clean-energy vehicle purchase incentives. (These policies will be discussed in more depth in the following chapter).

By 2050, when British Columbia is expected to reach its end target of an 80% reduction in GHG emissions from 2007 levels, the population is projected to have grown by 30%, from 4.7 million to over 6 million people (BC Stats, 2015a). This large increase in population size and resulting energy demand could pose significant threats to meeting the GHG emissions reduction targets if robust policy measures are not already firmly established, especially in the transportation sector.

In 2000 there were 2.2 million light-duty vehicles on the road in British Columbia and by the end of 2015 there were 2.8 million, showing an average annual growth rate of 1.6% (Statistics Canada, 2015). Between 2000 and 2009, the average annual distance travelled per light duty vehicle decreased from around 15,000 km to just under 13,000 km (Natural Resources Canada, 2011). Furthermore, since the Climate Action Plan, and associated policies affecting vehicle and fuel use, were implemented in 2008 and onward, per capita gasoline and diesel sales have decreased (Rivers & Schaufele, 2015), and so has the carbon intensity of the transportation fuel mix (BC Ministry of Energy and Mines, 2014). However, due to the steady increase in the vehicle stock, emissions from light duty vehicles in the province have shown only a minor reduction (BC Provincial Government, 2014). Assuming that the vehicle stock will continue to grow along with population growth and GDP growth in the province, then seeing deep reductions in GHG emissions from the personal transportation sector will likely require significant policy intervention.

1.2 Thesis objective

The IPCC suggests four main opportunities for mitigating emissions from transportation: (1) avoiding journeys where possible, (2) modal shift to lower-carbon transport systems (e.g. public transport, walking and cycling), (3) lowering the energy intensity of travel (through increased engine performance and use of lightweight materials), and (4) reducing carbon intensity of fuels (by substituting oil-based fuels with lower emission alternatives such as natural gas, biofuels, electricity, or hydrogen produced from low GHG emitting energy sources) (Sims et al., 2014).

Ultimately, reducing GHG emissions embodied in transportation implies decreasing the use of fossil fuels. Literature suggests this can be approached in a number of ways. *Transportation demand management* strategies aim to reduce emissions by decreasing total vehicle travel (addressing (1) and (2) from IPCC's suggestions); *Cleaner vehicle* strategies do not emphasize reduced travel, but aim to reduce emissions per kilometer of driving through efficiency improvements or switching to alternative fuels (addressing (3) and (4) above) (Litman, 2013); and a *comprehensive strategy* is a combination of both the aforementioned strategies (addressing all 4 of the IPCC's recommendations) (C. Yang et al., 2009).

The objective of this thesis is to assess a *cleaner vehicle* strategy for the personal transportation sector in British Columbia. Thus, we focus for the most part on technological possibilities for reducing GHG emissions. The two possibilities explored in depth here are electric vehicle adoption by consumers, and increased integration of biofuels into the fuel mix for conventional vehicles. The price of fuel is considered, but only insofar as it influences vehicle choice, fuel choice, and minor fluctuations in average vehicle travel. Furthermore, modal shifts in personal mobility from mass transit improvements and investments in cycling and walking infrastructure are recognized by the author as important and vital solutions for mitigating GHG emissions, but are outside the scope of this study.

The following research addresses the questions: (1) What is the potential for reducing GHG emissions from light duty vehicle travel through increased electric vehicle adoption, and increased integration of biofuels into the transportation fuel mix in British Columbia? (2) What policy measures can help to foster a transition towards electricity and biofuels as transportation fuels in British Columbia?

1.3 Introduction to methods

A conceptual model was developed using systems analysis and system dynamics theory to identify leverage points for policy intervention in British Columbia's light duty vehicle system. In order to quantify the impacts of various policy efforts on GHG emissions from light duty vehicle travel, a computer model was built using the system dynamics software, STELLA®, that simulates the light duty vehicle and fuel markets in British Columbia up to the year 2050.

1.4 Thesis structure

The remainder of this thesis is structured as follows:

- Chapter 2: Background literature, British Columbia's policies, introduction to system dynamics, and significance of research.
- Chapter 3: Methods: describes the conceptual model and the STELLA® computer model built for the purpose of this study.
- Chapter 4: Results and outcomes from modelled scenarios.
- Chapter 5: Discussion of results and policy recommendations.
- Chapter 6: Conclusion.

2 Background

2.1 Electric vehicles

While conventional vehicles are powered by burning gasoline or diesel in an internal combustion engine, electric vehicles (EV) are powered either fully or partly by a battery, which is charged from plugging in to the electricity grid. EVs include full battery powered electric vehicles that operate exclusively off of electricity from an externally charged battery, plug-in hybrid electric vehicles that can operate off of an externally charged battery alone or by a combination of battery and an internal combustion engine, and range-extended electric vehicles that are electric powered but contain an internal combustion engine that can charge the battery once its power is depleted to a certain level (Graham-Rowe et al., 2012). Non plug-in hybrid electric vehicles, since their battery is charged through the combustion engine and not by plugging in, will not be considered here as EVs and instead are considered as higher fuel-efficient conventional vehicles.

When operating in all-electric mode, EVs offer a 100% reduction in gasoline or diesel consumption compared to conventional vehicles. This can benefit the driver through reduced fuel costs, and benefit the environment through reduced exhaust emissions. In an area like British Columbia, where the electricity used to charge EV batteries comes almost entirely from low-carbon power generation, EV adoption has great potential for reducing GHG emissions from personal vehicle use.

Plug-in hybrid and range-extended electric vehicles are gaining in popularity as alternative vehicle choices, as they offer the benefits of driving in an all-electric mode, while retaining the convenience and assurance of added driving range and of being able to refuel quickly using traditional (gasoline or diesel) fuelling infrastructure. However, these types of plug-in vehicles that also use liquid fossil fuels can be seen as a temporary solution on the road to widespread adoption of zero-emission vehicles (Amjad et al., 2010). Hydrogen fuel cell vehicles, while showing future potential as a commercially viable zero-emission vehicle, still require significant improvements in fuel production, storage, and infrastructure in order to gain momentum (Sharma & Ghoshal, 2015), and addressing these aspects is outside the scope of this study. Therefore, for the remainder of this thesis, emphasis will be placed mainly on full battery electric vehicle adoption for integration of zero-emission vehicles into the light duty vehicle stock. Unless otherwise stated, in all the following text, 'EV' refers to battery electric vehicles only.

2.1.1 Comparing EVs and conventional vehicles

British Columbia boasts a low price for electricity (the highest residential rate is 11.95 cents per kWh), produced mainly by hydroelectric generation, which is a relatively low-carbon source of energy (BC Hydro, 2016). Therefore operating costs for EV are minimal when compared to gasoline prices, as are the GHG emissions of electricity generation when compared to burning gasoline. To illustrate, driving the fully electric Nissan Leaf for 15,000 km over one year would cost about $360 in electricity charges and result in 0.03 tons CO_2e (carbon dioxide equivalent) in GHG emissions. By contrast, driving an average compact gasoline powered vehicle the same distance would cost around $1,300 (based on 2015 gas prices) and release over 3 tons of CO_2e (author calculations, assumptions discussed in chapter 3). Thus, even at the highest price for electricity, driving an EV can offer a 72% reduction in fuel costs and up to a 99% reduction in end-use GHG emissions compared to a similar sized conventional vehicle.

The potential economic and environmental advantages of EVs over conventional vehicles, however, currently come at a cost. Generally, EVs have a higher purchase price than an equivalent gasoline engine model due to high production cost of the batteries (Poullikkas, 2015). Furthermore, limited driving range and long charging time compared to conventional vehicles can lower the perceived utility of EVs compared to conventional vehicles (Neubauer & Wood, 2014). Table 2.1 summarizes the retail price, driving range on a fully charged battery, charging time, and fuel efficiency for two of the most popular EVs compared to a typical gasoline hybrid-electric vehicle (Toyota Prius), and a Honda Civic—consistently the most popular conventional gasoline powered light duty vehicle in Canada.

Table 2.1 Comparison of performance and price factors for popular EV, hybrid and conventional vehicles.

Vehicle (2016 model year)	**Retail price** (2016, Canadian $)	**Driving range** (full charge/tank, km)	**Charging time** (240 volt)	**Fuel efficiency**[e] (L/100km equiv.)
Tesla Model S 90D[a] (90 kWh battery)	119, 400	460	10 hours	2.6
Nissan Leaf SV[b] (30 kWh battery)	37, 398	172	4 hours	2.1
Toyota Prius[c] (Gasoline hybrid)	25, 995	946	0.2 hours[f] (refuelling)	4.5
Honda Civic LX[d] (gasoline)	20, 807	698	0.2 hours[f] (refuelling)	6.7

a. Ref: (Tesla Motors, 2016)
b. Ref: (Nissan, n.d.)
c. Ref: (Toyota, n.d.)
d. Ref: (Honda, 2016)
e. Ref: (EPA, n.d.)
f. Author's estimation

The Honda Civic achieves significantly more range on a full tank than both the Nissan Leaf and the Tesla Model S, and comes at a purchase price nearly half that of the Leaf. Since the Tesla Model S is a luxury vehicle it is irrelevant to compare its price to the other vehicles, as they are very unlikely to compete for sales. The hybrid Toyota Prius, while requiring gasoline to operate, combines the qualities of electric vehicle and conventional vehicle to achieve significantly longer range than all the vehicles compared, and is priced between the Civic and the Leaf. The Prius' added range and increased efficiency compared to the Civic come from operating on battery power only while stopped or at very low speeds. But notice that the Leaf and the Model S are significantly more efficient still than the Prius and the Civic. A technological advantage of EVs over conventional vehicles, is that they operate with much higher efficiency, especially in city driving conditions where EVs do not consume energy while not moving and can charge their battery through regenerative braking (Karabasoglu & Michalek, 2013).

Both the Prius and the Civic are refuelled conventionally and estimated to take about 12-15 minutes. The charging times for the EVs are much longer, but not necessarily important for day-to-day use since these can be easily achieved over night, and with the exception of holiday trips a vehicle is not likely to exceed 172 km, let alone 460 km, in a day. Thus charging will rarely occur from zero if due diligence is paid to daily charging.

Environmental concerns exist around the resource intensive production of lithium-ion EV batteries. Particular concern surrounds meeting the increased demand for the metals, lithium and cobalt from finite resources (Simon et al., 2015), and the environmental impact of sourcing the metals and constructing the battery (McManus, 2012). A comparative lifecycle assessment of EVs and conventional vehicles found that while EVs can offer significant reductions in global warming potential in their use-phase (when powered by low-carbon electricity), their production phase can exhibit twice the environmental impact of a conventional vehicle (Hawkins et al., 2013). This is due to the heavy resource intensity from the production of lithium-ion batteries standard in EVs. Therefore battery lifetime is an important factor in the environmental impact over the lifetime of an EV. Hawkins et al. (2013) find that when the lifetime of a battery is reduced to 100,000 km, the environmental benefit of an EV shows only a minor improvement over a gasoline vehicle, due to the high impact of the EV production-phase. Therefore, complete lifecycle assessments should be necessary in order to quantify the complete impact of an EV over its lifetime

Concern may also be expressed over the increased electricity demand from widespread adoption of EVs, particularly during peak charging hours in the evenings and overnight (Axsen et al., 2015). Such spikes in electricity demand could cause problems by exceeding the capabilities of the electricity grid, but smart-metering infrastructure exists that can stagger charging intensities and redistribute the load (Poullikkas, 2015). Thus thoughtful city planning will likely be necessary if EVs are to capture a significant portion of the vehicle market.

2.1.2 Barriers and drivers

Rezvani et al. (2015) provide a comprehensive overview of the drivers and barriers that influence electric vehicle adoption. The study finds that consumer perception of EVs is a major factor in limiting the adoption of the technology. Many consumers are not aware of, or properly informed about, the operation of EVs, and thus do not consider them as viable options for purchase.

To date, most alternative fuel vehicle studies have focussed on hybrid electric vehicle adoption (until recently the only major commercial scale alternative vehicle), but lessons from these studies need to be approached cautiously (Rezvani et al., 2015). As hybrids do not need to be plugged in, they do not require different user behaviour from conventional vehicles. So, while hybrid-electric vehicle studies can be helpful in gauging the acceptability of electric vehicles, studies focussing solely on plug-in electric vehicles, are of utmost importance, as they require a significant change in user behaviour, namely to do with battery charging. Understanding consumer response to changing requirements for private mobility, especially among subjects who have first hand experience with EVs, is a key area in explaining the limited adoption of the technology. Literature recommends that further efforts to understand the psychological and emotional behaviour of consumers, with regard to EV adoption, would greatly benefit policy makers working to overcome the barriers (Rezvani et al., 2015).

One psychological effect, the “neighbour effect,” (Axsen et al., 2009; Mau et al., 2008) suggests that new technology—in this case, alternative fuel vehicles—becomes more attractive as its visibility in the market increases. Applying this knowledge to EV adoption, we could assume that in the early stages, policy is required to promote the initial uptake of EVs in order to ‘get over the hump’ and allow the neighbour effect to take hold.

Axsen et al. (2015) places the barriers against EV adoption mainly on the lack of availability and consumer choice in dealerships. Based on a study of surveys of mainstream vehicle buyers and current owners of plug-in electric vehicles in Canada, Axsen et al. (2015) estimated the unconstrained demand for plug-in vehicles in British Columbia to reach 32% of the market share in 2020. However, when constrained by home charging access, dealership availability, vehicle model selection and variety, and familiarity, the demand is reduced to only 1% of sales in 2020. As lack of availability and variety of EV models are seen to be the largest constraint against EV demand, the researchers recommend that supply-side policy measures, similar to the Zero Emissions Vehicle (ZEV) mandate in California (discussed later) are essential to realize the potential for significant EV adoption.

Furthermore, “range anxiety” or the perceived limited driving range of an EV compared to a conventional vehicle can play a major part in limiting the acceptance of EVs as a purchase option (Neubauer & Wood, 2014; Rezvani et al., 2015). Referring back to table 2.1, a comparable sized gasoline vehicle can achieve more than 3 times the mileage of an EV on a full charge. However, if the EV is used for day-to-day errands and commuting, it is unlikely to exceed its maximum range in a day, and thus home charging access would generally be sufficient. Nevertheless, Neubauer and Wood (2014) find that workplace charging as well as widely available public charging access can significantly reduce the effect of range anxiety.

2.1.3 Case study of EV adoption in Norway

Norway is a standout example of fostering adoption of electric vehicles through government incentives. In 2015, approximately 18% of all new car sales in Norway were electric powered vehicles, bringing the total registered EVs to 70,000, or roughly 2% of the total passenger vehicle fleet—by far the highest market share of any country in the world and expected to increase over the next few years (Bjerkan et al., 2016). This can be attributed to significant financial incentives that lower the purchase price of EVs to that of a comparable conventional vehicle, as well as further incentives that improve the convenience and cost-effectiveness of driving an EV over an internal combustion engine vehicle (Bjerkan et al., 2016).

While only achieving significant success in the last few years, Norway’s efforts to develop and encourage EV use have been in place since the 1970s. Figenbaum et al. (2015) divide Norway’s EV progress into five phases: (1*) Concept development (1970-1990)*, (2) *Testing (1990-1999)*, (3) *Early Market (1999-2009)*, (4) *Market introduction (2009-2012)*, and (5) *Market expansion (2013-present).* Over the course of these phases, many incentives were gradually implemented—from development grants, to exemptions from vehicle registration fees, purchase taxes, road tolls, and ferry tickets, to reduced annual license fees, to access to bus lanes and free parking and battery charging in urban centres (Holtsmark & Skonhoft, 2014). However, real results were not seen until the most recent *market expansion* phase where advances in EV performance along with increased variety and retail stock of EV models provided the opportunity for widespread consumer adoption (Figenbaum et al., 2015).

In a survey of 3400 EV owners in Norway, Bjerkan et al. (2016), found that their sample was dominated by middle-aged men, highly educated, with a high income, and living in the capital area. This corresponds to typical characteristics of EV adopters, as well as the characteristics of general *new* vehicle owners in similar types of studies (Bjerkan et al., 2016; Figenbaum et al., 2015). Also, studies find that most EVs are purchased by consumers living in multi-car households (Figenbaum et al., 2015). This suggests that also having access to a conventional vehicle might make purchasing an EV more likely.

In terms of incentives for purchasing an EV, Bjerkan et al. (2016) found that the upfront cost reduction from tax exemptions was the most important factor in EV adoption, although many respondents chose access to bus lanes, or exemption from road tolls as their *only* critical incentive for EV purchase. Therefore a wide variety of incentives may be necessary to convert all potential buyers into actual EV adopters and thus realize the maximum benefit from widespread EV adoption.

Potential benefits of EV adoption in Norway come mainly in the form of reducing local air pollution and reducing GHG emissions. Very similar to British Columbia, 98% of Norway's electricity production comes from renewables and almost all of it is hydroelectric power (Statistics Norway, 2016), thus widespread adoption of EVs offers great potential for lowering domestic GHG emissions. However, although EV adoption is increasing rapidly, their share of the overall vehicle fleet is still small, and GHG emissions from road traffic still increased (albeit only 0.8%) between 2013 and 2014 (Statistics Norway, 2015). Figures from 2015 were not yet available on the Statistics Norway website.

Some literature questions the overall effectiveness of implementing generous EV promoting policies like those in Norway. Holtsmark and Skonhoft (2014) find that the Norwegian policy may not be offsetting conventional vehicle purchases with EVs, but may encourage families to purchase an EV as an *extra* car on top of their conventional vehicle. The same study argues that EV owners are less likely than non-owners to opt for public transport or walking and cycling, due to the added driving convenience from the EV policies in place, and that this perpetuates the problematic private transportation system while reducing the demand for investment in mass transit improvements that could benefit an entire population. Aasness and Odeck (2015) find adverse effects from Norway's policies include increased congestion and travel time in public transit lanes (from EVs being allowed access to these lanes) as well as significant lost revenue from taxes, tolls, and registration fees. Holtsmark and Skonhoft (2014) calculated that the amount paid in EV subsidies added to the lost revenue as a result of tax and fee exemptions could have bought enough carbon credits to make Norway 'carbon neutral' in 2013. Also—of particular importance to implementation of similar EV policies in other countries—the environmental benefits of EVs are dependent on the type of electricity generation used to charge the vehicle's battery. Where the electricity to power EVs is generated from coal or other fossil fuels, any reduction tailpipe GHG emissions can be negated by the emissions from added demand for fossil-based electricity production (Thomas, 2012).

2.1.4 EV policy and adoption in British Columbia

British Columbia has an incentive program in place that offers up to $5000 towards the purchase of a plug-in electric vehicle or a hydrogen fuel cell vehicle (New Car Dealers of BC, 2016), and a "scrap" program that offers $3250 towards the purchase of a plug-in hybrid or full EV with the trade-in of any conventional vehicle (BC SCRAP-IT Program Society, 2016), which can be combined for a total of $8250 in purchase incentives. Plus, the government has very recently granted access to high-occupancy vehicle lanes, as an added incentive to all EV drivers regardless of the number of passengers in the vehicle (Meissner, 2016).

The first phase of the CEVforBC (clean energy vehicles for BC) program, which ran from 2011 to 2014, spent $14.3 million towards point-of-sale incentives for the purchase of EVs, plug-in hybrids and fuel-cell vehicles, developing clean energy vehicle infrastructure, and funding research and outreach (British Columbia, 2015). Over the course of phase one, incentives were paid on 950 clean energy vehicles at an average of $4,800 per vehicle, 1,028 public and private EV charging stations were installed, and one new hydrogen fuelling station was added to the 4 existing. 610 of the 950 incentivized purchases were full battery EVs and the remaining were plug-in hybrids and range-extended electric vehicles (no sales of fuel cell vehicles were reported), thus showing a preference for EVs over other types of electric vehicles among the small sample of consumers.

Even before British Columbia implemented point-of-purchase incentives for electric vehicles through the CEVforBC program, tax rebates were issued on the purchase of new hybrid-electric vehicles in Canada. Chandra et al. (2010), using a cost-benefit analysis, found the cost to the government of CO_2 abatement to be very high, at $270/ton. Furthermore in all provinces offering tax rebates, 26% of the hybrid sales up to 2006 can be attributed to the incentives. This implies that a majority of the incentives were paid to consumers who would have already purchased a hybrid vehicle. Nevertheless the incentive increased the rate of adoption of hybrid vehicles.

It is interesting to note that over the course of the first phase of CEVforBC, purchasers of the Tesla Model S received over 20% of the total number of incentives (British Columbia, 2015). Since this is one of those most expensive EVs on the market, one might question whether more than one fifth of the incentives paid went to a consumer who is not as influenced by purchase price as someone with a lower income. At a base price over $100,000 (Tesla Motors, 2016), one can cast doubt whether or not a $5000 incentive might make any difference in a decision to buy. Thus, close evaluation of incentives is necessary to determine the most effective and cost-efficient strategies for encouraging the adoption of EVs.

Now in the second run of the CEVforBC program, the government has maintained the same dollar value for the incentives, but has limited incentives to only EVs under $77,000 (New Car Dealers of BC, 2016), thus ruling out the Tesla Model S from incentives at its current price tag as well as any other luxury EVs that may enter the market. Further investments in charging infrastructure and hydrogen fuelling infrastructure will be made, along with funding research and public outreach. The program will run either until March 31, 2018 or until the total budget of $7.5 million towards point-of-sale incentives is exhausted (BC Ministry of Energy and Mines, 2015). Based on the average incentive amount paid over the first run of the program, the purchase of over 1500 electric or hydrogen fuel cell vehicles could be incentivized in the 3 year span of the second run—representing less than 0.1% of the provincial light duty vehicle stock.

2.1.5 Future of EV promotion in British Columbia

Current recommendations to the BC Provincial Government suggest implementing zero-emission vehicle standards to ensure buyers have sufficient options for purchasing cleaner technologies (e.g. EVs and hydrogen fuel cell vehicles). For example, the government-instated Climate Leadership Team, whose task is to direct the government towards a new Climate Action plan, recommend the following sales targets for light duty zero-emission vehicles: 10% of sales by 2020; 22.5% by 2025; and 30% by 2030 (Climate Leadership Team, 2015). These standards echo the Zero Emission Vehicle (ZEV) standards in place in California.

When California introduced its ZEV standards in 1990, the goal was lofty— mandating minimum numbers of zero emission vehicle sales in order to influence technological innovation (at the time concerned mainly with EV) while shifting the costs of the transition onto manufacturers (Sierzchula & Nemet, 2015). The policy dealt greatly in uncertainty, as EVs were relatively undeveloped and their adoption relied heavily on assumptions about future technology and battery prices (Bedsworth & Taylor, 2007). Since the ZEV standards' implementation, average vehicle emissions have fallen in California, although progress is mainly attributed to concurrent State low-emission vehicle programs and fuel efficiency advancements in conventional vehicles (Bedsworth & Taylor, 2007). However with modern advances in zero-emission technology and the modest progress shown in British Columbia's CEVforBC incentive program, a Zero Emission Vehicle mandate could be within grasp for provincial policy measures. Furthermore, increased attention and sales of EVs may naturally increase the variety of EVs available and lead to more competitive pricing through natural market behaviour.

2.2 Biofuels

In efforts to reduce dependence on non-renewable fossil fuels, and to decrease the carbon intensity of the transportation fuel-mix, liquid biofuel development and inclusion in the fuel pool is garnering significant attention. Biofuels are generally considered to be lower-carbon alternatives to fossil fuels, and can be produced from renewable resources. The two most common biofuels in the on-road transportation fuel mix are *bioethanol* and *biodiesel*. *Bioethanol*, generally produced from starch or sugar-based crops (most commonly corn in the U.S. and Canada), can be blended with gasoline in order to offset gasoline demand, while *biodiesel* produced from vegetable oils, animal fats, or waste grease is a substitute for diesel fuel (Guo et al., 2015).

In British Columbia, almost all light duty vehicles are fuelled by gasoline—its consumption contributing to 98% of the GHG emissions from light duty vehicles in 2013 (BC Provincial Government, 2014). As it seems very unlikely that all gasoline burning vehicles will be replaced with zero-emission vehicles in the near future, incorporating alternative low-carbon liquid fuels into the existing fuelling infrastructure can play an important role in reducing GHG emissions. Furthermore, the carbon intensity of conventional gasoline and diesel fuels are expected to increase over time as petroleum extraction from dirtier resources, such as tar sands or shale, increases (Melaina & Webster, 2011). Thus, measures to incorporate lower carbon intensity biofuels into the transportation fuel mix could be of even greater importance in the future for reducing GHG emissions.

Worldwide, ethanol is currently the most commonly used biofuel in the transportation fuel mix and, along with biodiesel, it is most likely to remain the dominant biofuel in 2050 (Guo et al., 2015). The same is true in Canada, where ethanol must comprise a minimum of 5% of the gasoline-class fuel sales, and biodiesel at least 2% of the diesel-class fuel sold (Canadian Environmental Protection Act, 2010). Nearly all Canadian light duty vehicles are gasoline powered (Natural Resources Canada, 2011), thus in the context of substituting fossil fuels with biofuels, those compatible with gasoline engines have the greatest potential for adoption following the current path. The following introduces three options available for offsetting gasoline demand in light-duty internal combustion engine vehicles: first-generation bioethanol, second-generation bioethanol, and "drop-in" biofuels.

2.2.1 Bioethanol

Bioethanol is an alcohol derived from biomass (plant matter) that has similar combustion properties to gasoline and can be blended into the fuel mix to offset gasoline demand from combustion-engine vehicles (Guo et al., 2015). Up to a concentration of 15% ethanol by volume (E15), ethanol-gasoline blends are considered compatible with most gasoline-only engines (Szulczyk et al., 2010). Flexible fuel (or "flex-fuel") vehicles are increasing in production and contain an internal combustion engine that can operate on gasoline only, or gasoline-ethanol blends up to E85 (85% ethanol, 15% gasoline) (Anderson et al., 2012).

The energy density of ethanol is approximately 67% that of gasoline (Guo et al., 2015), meaning about 1.33L of pure ethanol would be needed to produce the amount of energy in 1 L of gasoline. So as the ethanol concentration in the fuel is increased, the fuel efficiency of a vehicle worsens relative to operating on pure gasoline. For example, a vehicle operating on E5 (5% ethanol by volume) may see a 1-2% decrease in fuel efficiency compared to gasoline, and a vehicle using E85 might incur a 28% reduction in efficiency.

When burned, bioethanol releases only the carbon stored in the vegetative biomass over its lifetime. Thus in terms of use-phase emissions, bioethanol, and biomass in general, can be considered carbon-neutral fuels, as the carbon emitted is carbon previously sequestered from the atmosphere and (if the harvested biomass is replanted) will be sequestered by future biomass growth. The emissions associated with bioethanol come from its production and are discussed in the following sections.

2.2.2 First generation bioethanol

Almost all of today's bioethanol comes from agricultural-based feedstocks—most commonly corn in the U.S. and Canada—and is referred to as a "first generation" biofuel as its production competes with food production (Ho et al., 2014). Starch or sugar based crops (e.g. corn, wheat, sugarcane) are converted into ethanol by extracting and fermenting the sugars they contain (Guo et al., 2015).

In government policy, first-generation bioethanol is generally reported to have lower carbon intensity than gasoline. A report for the U.S. government found corn ethanol to offer a 19-48% reduction in lifecycle GHG emissions compared to gasoline (M. Wang et al., 2012). In British Columbia, the latest report lists the carbon intensity of the ethanol supplied at 41% below that of gasoline (BC Ministry of Energy and Mines, 2014). However, while generally regarded in government policy as a lower-carbon alternative to fossil fuels, the real life-cycle emissions from first-generation bioethanol can take on a wide range of values, from significantly less than, to significantly greater than the full life-cycle emissions from gasoline, depending on the study (Djomo & Ceulemans, 2012).

The reported carbon intensity of first generation bioethanol not only varies depending on how it is produced, but also on the system boundary of its life cycle assessment (Shonnard et al., 2015). While emissions are counted from the direct production of ethanol, they may also extend to the land-use change either *directly,* as a result of converting forest or grassland to cropland for ethanol feedstock, or *indirectly*, as a result of establishing new croplands to replace the cropland converted to biofuel production (Searchinger et al., 2008). This conversion of land can be counted towards the lifecycle GHG emissions of bioethanol through carbon released in the conversion of forest or grassland to cropland, and loss of sequestration potential from the converted land. A review of 15 studies on the carbon intensity of first generation bioethanol due to indirect land-use change found a range from -29% to 384% the carbon intensity of gasoline (Djomo & Ceulemans, 2012).

Due to concerns over the lifecycle impacts of first-generation bioethanol and due to limits to production potential for meeting fuel demand, emphasis is being placed on the development of second-generation, or lignocellulosic, bioethanol (Fargione et al., 2008; Ho et al., 2014; Y. Yang et al., 2012).

2.2.3 Second generation bioethanol

Second-generation bioethanol, from non-food, lignocellulosic plant materials (e.g. forest and crop residues, dedicated energy crops grown on marginal land) are emerging as a promising solution to the issues associated with first-generation biofuels (Guo et al., 2015; M. Q. Wang et al., 2011). Lignocellulosic bioethanol, particularly derived from forest residues could have great significance not only for reducing GHG emissions, but also as a potential industry in British Columbia where forestry is a major resource.

Lignocellulosic processing, which extracts sugars from the structural material in the cell walls of plants in order to make second-generation bioethanol, is more complicated than the production of first-generation bioethanol, but can prove more beneficial by drawing from a variety of feedstocks that do not disrupt food supply or cause significant impacts from land-use change (Mabee & Saddler, 2010).

A review of 53 life cycle assessments of lignocellulosic bioethanol found that, with the exception of 2 studies, all reported significant reduction in GHG emissions compared to fossil fuel use (Borrion et al., 2012). The results showed a range of GHG reductions from 4% to 15% for E10, and 12% to 96% for E85, when compared to conventional gasoline. Therefore, while second generation bioethanol is generally agreed to be an improvement over first generation bioethanol and fossil fuels, some uncertainty persists in the real lifetime carbon intensity of lignocellulosic ethanol, with differences in methodology reflecting the differences in measured life-cycle impacts.

Currently, the main barrier to commercial viability of lignocellulosic bioethanol is in the conversion of cellulose and hemicellulose to sugar (Guo et al., 2015). The process is more complex and costly than that for first generation biofuels. Economic arguments aside, Mabee and Saddler (2010) find that agricultural residues can yield between 110 and 280 L ethanol per dry ton of biomass, while wood residues could yield between 120 and 300 L. Another study reports that a number of pilot cellulosic ethanol plants are yielding between 257 and 315 L/dry ton of feedstock, compared to first generation production that yields 372 to 432 L/dry ton of corn (Guo et al., 2015).

Another benefit of second-generation bioethanol production comes in the by-products of the process. A key factor in lignocellulosic ethanol production is the separation of cellulose and hemicellulose (from which the sugars are derived) from lignin. In a cellulosic ethanol plant, after cellulose and hemicellulose are removed and fermented into ethanol, the remaining lignin material can be burned to generate enough electricity to power the entire operation—possibly making the plant a net-exporter of electricity (M. Q. Wang et al., 2011).

2.2.4 Drop-in biofuel

Another future option for replacing gasoline with low-carbon alternatives lies in the development of “drop-in” biofuels. Drop-in biofuels—called so because they can literally be “dropped in” to the tank as a perfect substitute for gasoline or diesel—are still in a research and development stage, but offer potential as an easily integrated alternative to liquid fossil fuels (Guo et al., 2015). While bioethanol must be blended with gasoline in order to work in modern engines, and require the installation of additional fuelling infrastructure, alternative biofuels are being developed that do not require any changes to the current technology.

Forest-derived drop-in biofuels could be of particular interest to British Columbia, as they could be combined with the current forestry industry. A life-cycle assessment of a prototype forest-derived bio-gasoline showed a lifetime carbon intensity of 0.156 kg CO_2e/L (Halog & Bortsie-Aryee, 2013). Assuming the same energy density of a litre of gasoline, this result shows the potential for a forest-derived biogasoline to reduce GHG emissions by up to 95% when compared to gasoline. However, as significant advances need to be made in order to make drop-in biofuels viable, their discussion ends here.

2.2.5 Renewable and low carbon fuel policies in British Columbia

As part of British Columbia’s efforts to reduce GHG emissions and to reduce reliance on non-renewable fuels, the Renewable and Low Carbon Fuel Requirements Regulation (henceforth RLCFRR or ‘the regulation’) came into force in 2010, obligating fuel suppliers to include 5% renewable content in their gasoline pool and 4% renewable content in their diesel pool, as well as to decrease the carbon intensity of their overall fuel mix by 10% between 2012 and 2020 (British Columbia, 2008). The regulation does not set requirements for what particular renewable fuels must be used, only the percentage of the fuel pool that must be fulfilled by renewables. The 5% renewable content in the gasoline pool is already easily accounted for in the nationally mandated E5 minimum if the ethanol is sourced from renewables. At present (to the best of the author’s knowledge) only one service station in British Columbia offers E85 (Arcade Station, n.d.).

If higher ethanol blends are to be stocked by retailers, it is important that their prices reflect the decrease in fuel efficiency resulting from ethanol’s lower energy content compared to gasoline. Thus if consumers are given the choice of which fuel to put in their flex-fuel engine, it is recommended that ethanol be priced at less than 70% of the gasoline price in order to keep ethanol competitive in the face of lost efficiency (Ferreira et al., 2009).

Fuel suppliers in British Columbia reported an average carbon intensity of 53.11 gCO_2e/MJ for ethanol in the fuel mix in 2012, compared to 90.21 gCO_2e/MJ for gasoline, and ethanol accounted for 5.8% of the gasoline grade sales (BC Ministry of Energy and Mines, 2014). According to the most recent government report, in 2012 the changes to the gasoline and diesel pools resulted in the avoidance of 904,868 tons CO_2e in GHG emissions (BC Ministry of Energy and Mines, 2014). However, these standards apply to all fuels sold for heating as well as transportation, so not all of the emissions avoidance can be awarded to the transportation sector, and the relative distribution of biofuels to each sector was not made available.

As per promoting second-generation biofuels, a renewable fuel standard alone does not necessitate their pursuit by retailers if their price is not competitive with conventional food-stock based biofuels. However, instituting a low carbon fuel standard on top of a renewable fuel standard can help shift the biofuel mix towards those with lower carbon intensity, thus bolstering development of second-generation biofuels (H. Huang et al., 2013). Thus the British Columbia provincial government is on the right track with its regulation that mandates not only increased renewable fuels in the fuel mix, but also a decrease in carbon intensity. H. Huang et al. (2013) also note that a carbon tax can help shift the market towards biofuels, however cellulosic biofuels will only be favoured over first-generation biofuels if carbon is priced extremely high.

2.2.6 Bioethanol opportunities for British Columbia

A report evaluating British Columbia's potential for electricity generation from wood based biomass resources estimated the available surplus volume of biomass from sustainable forestry harvest to be about 27 million m^3 per year in 2013, decreasing to 10 million m^3 per year in 2025 and thereafter due to forecasted changes in activity (BC Hydro, 2013). Using a conversion of 2.45 cubic metres of wood to 1 oven-dry ton (the same conversion employed by the report), then based on the range of potential yields of bioethanol from bioconversion of lignocellulosic feedstocks discussed by Mabee and Saddler (2010) and Guo et al. (2015), British Columbia's forests could yield between 1.3 and 3.5 billion litres of ethanol in 2013, decreasing to between 0.5 and 1.3 billion litres of bioethanol per year in 2025 and thereafter. These figures are from excess wood resources *alone,* and do not assume that procuration of energy biomass will subtract from any of the total forestry product. Thus, the ranges represent a lower bound for the provincial bioethanol production potential in keeping with the forecasted annual forestry product demand. However, other wood energy purposes such as electricity generation or wood-pellet production may compete with, and reduce the viability of, bioethanol production from forestry residues (Ackom et al., 2010).

Another study places the total ethanol production from BC's renewable forestry residues at 1.8 billion litres per year (Mabee et al., 2011). Furthermore, Yemshanov et al. (2014) estimate the roadside harvest residues supply in British Columbia to be between 0.49 and 10.22 million dry tons/year depending on a range of ecological, economic, and technical constraints, which translates to between 0.06 and 3.1 billion litres of bioethanol depending on the efficiency of the process.

Challenges that need to be overcome for widespread commercial production of cellulosic ethanol include the high energy consumption of biomass pre-treatment, efficiency of sugar extraction from biomass, and scaling up processes to commercial supply volumes (Zhu & Pan, 2010). Van Heiningen (2006) finds that some of these challenges may be overcome through the conversion of pulp mills into "integrated forest biorefineries" that can produce ethanol along with other products from the cellulosic and hemicellulosic waste generated in the pulping process.

Competitiveness with outside markets is also a barrier to establishing domestic bioethanol production. For an optimally located forest-based bioethanol plant in British Columbia, Stephen et al. (2013) estimate the minimum ethanol selling price (at which the producer would break even) to be \$1.02 /L compared to an import cost below \$0.75 /L for Brazilian produced cellulosic ethanol. This suggests that promoting local production can result in higher prices for the consumer, hindering the attractiveness of bioethanol over gasoline (Stephen et al., 2013). So, either government incentives of over 25% of the production price of BC bioethanol, or taxes over 36% on imports in order to make the domestic product competitive may be necessary.

Despite the opportunities present in the forestry sector, there are currently no commercial cellulosic ethanol projects in development in British Columbia (USDA Foreign Agricultural Service, 2015). Cellulosic bioethanol development in BC would require significant investment in infrastructure and research and development. Great volumes of feedstock are readily available from forestry residues, thus land-use issues and growing of feedstock should not limit the initial uptake of a biofuel industry. Vehicle compatibility, namely the adoption of flex-fuel vehicles in the light duty vehicle fleet, also does not pose a significant barrier to higher-blend ethanol-gasoline fuel use, as the upgrade to flex-fuel engines comes at a small price and can easily penetrate the vehicle market (Du & Carriquiry, 2013). Gasoline fuelling stations would require upgrades or retrofits to offer higher ethanol blends—a blender-pump exists that draws gasoline and ethanol from two separate storage tanks and allows the consumer to select the desired ethanol content of the fuel (Yanowitz et al., 2013). Also, ethanol would need to be priced at less than 70% the price of pure gasoline in order to make it competitive. This could be a significant barrier to a bioethanol industry as initial production costs would be high, leading to either high consumer costs or large subsidies for domestically produced bioethanol.

As shown, there is great uncertainty in the amounts of bioethanol that can be produced from British Columbia's forests and the feasibility of its production, especially once economic, ecological, and technical factors are considered. The majority of these factors are outside the scope of this study, but deserve mention, as they are integral in discussion surrounding a domestic biofuel industry. Producing bioethanol in British Columbia from forestry residues would help to reduce the reliance on imported transportation fuels, as well as remove some of the uncertainties inherent in the production and consumption of first-generation biofuels. The work presented here aims to project the demand for biofuels—particularly second-generation bioethanol—and the associated potential GHG emissions from its consumption over gasoline. Feasibility of establishing an industry is left to other studies.

2.3 Tank-to-wheel versus well-to-wheel emissions

British Columbia’s Renewable and Low Carbon Fuel Requirements Regulation requires that retailers consider the entire lifecycle of the fuels in calculating their carbon intensity (British Columbia, 2008), and reductions in carbon intensity may be seen by incorporating second-generation bioethanol into the fuel mix in place of first-generation ethanol or gasoline. However, based on British Columbia’s GHG inventory practices these changes will have no effect on the reported annual emissions. This is because the GHG inventory for British Columbia is based only on the CO_2e released when a fuel is burned, and not the impact over its entire lifecycle (BC Ministry of Environment, 2014b). The approach employed by BC is called a ‘tank-to-wheel’ assessment of emissions, meaning only the end-use of the fuel (from the gas tank to the wheels) is accounted for. The provincial government uses constant emission factors of 2.299 kg CO_2e/L of gasoline, and 1.504 kg CO_2e/L of ethanol (BC Ministry of Environment, 2014b), which works out to approximately equivalent amounts of GHG emissions per unit of energy once ethanol’s lower energy density is taken into consideration. Using full lifecycle, or ‘well-to-wheel’ analysis, the total emissions from the fuel’s sourcing to its burning are considered, and therein can more robust distinctions be made between lower and higher carbon intensity fuels.

Granted, well-to-wheel emissions are used to calculate the carbon intensity of fuels under the RLCFRR in British Columbia, so improvements in lifecycle emissions from fuels can be quantified and realized within the province. But it is worth noting that the two reporting systems—RLCFRR (British Columbia, 2008) and the GHG Emissions Inventory Report (BC Ministry of Environment, 2014b) are at present incompatible. Therefore, for the remainder of this thesis, emphasis will be placed on the lifetime, or well-to-wheel, emissions from transportation fuels. Tank-to-wheel emissions will only be used or discussed when it is deemed necessary to make a comparison.

2.4 System dynamics

System dynamics is the study of feedback, interactions, and causal effects to analyze and explain complex systems. Because climate policy scenarios can have many interacting forces at play (e.g. human behaviour and technological advances, energy consumption and energy costs) system dynamics is well suited to address the interactions and feedback loops inherent in these systems. Ghaffarzadegan et al. (2011) describes several areas where using small system dynamics models can help to overcome frequent problem areas in public policy-making. The feedback approach of system dynamics can help to expose counterintuitive behaviour, wherein a system exhibits resistance to policies that look like they should be effective. Furthermore, using aggregate data and few stocks and flows, allows for rigorous experimentation that would otherwise be complex and costly, while the relative simplicity of system dynamics models allows for greater understanding for everyone, not just the modellers.

Of utmost importance in developing effective policy is recognizing the phenomena of *policy resistance,* wherein a system does not respond intuitively to policy measures, and *policy synergy*, wherein complementary policy measures can help to overcome resistance (Stepp et al., 2009). Stepp et al. (2009) illustrate with causal loop diagrams (an integral tool in system dynamics theory discussed in the following chapter) the dynamic interactions between components in the light duty vehicle market in the U.S. Their work clearly highlights the rebound effect of increased fuel efficiency resulting in greater vehicle miles traveled (as an example of *policy resistance*), and how also increasing the price per mile by raising fuel taxes can act as a *policy synergy* with increased fuel efficiency to combat the resistance and more effectively reduce GHG emissions.

There are a significant number of studies using system dynamics to model climate and transportation scenarios. The interactive policy tool, C-ROADS, uses system dynamics to model GHG emissions and the climate in response to policy scenarios across all sectors (Sterman et al., 2012), and so does the FREE behavioural climate-economy model (Fiddaman, 2002). Several studies have used system dynamics to model GHG emissions embodied in transportation in urban centres (Feng et al., 2013; Liu et al., 2015), and in inter-city transport (Han & Hayashi, 2008). The system dynamics model, UniSyD_IS, was used to compare transition pathways to alternative renewable based transportation fuel systems in Iceland (Shafiei et al., 2015). Struben and Sterman (2008) analysed positive feedbacks that can both enable and constrain the diffusion of alternative fuel vehicles in the auto market. Similarly, Kwon (2012) used a system dynamics model to assess management strategies for overcoming market barriers to alternative fuel vehicle adoption.

Several studies have used system dynamics to model biofuel production and market development in the U.S. (Y. Huang et al., 2010; Vimmerstedt et al., 2012), and in Europe (Barisa et al., 2015; Sanches-Pereira & Gómez, 2015), as well as modelling land-use change from biofuel development (Warner et al., 2013). To the best of the author's knowledge, a system dynamics model has not been developed that combines EV diffusion and biofuel development in a Canadian context.

2.5 Significance of research

The objectives of this study are twofold. First, is to use system dynamics to examine the GHG emission reduction potential of two prominent alternative fuel technologies. The second is to investigate a potential pathway to a low-carbon personal transportation system in British Columbia in order to help the provincial government in developing policy to reduce GHG emissions. By using system dynamics and systems thinking to develop the model used here, I propose that the end result is a transparent and applicable policy assessment tool that can aid not just policy-makers, but the public in understanding the complex issues that can arise from behavioural systems such as vehicle and fuel markets.

3 Methods

System dynamics and the computer software STELLA® were used to model the GHG emissions from light duty vehicle use in British Columbia under various scenarios. The key areas of interest in this study were the market penetration of EVs and integration of bioethanol into the liquid fuel mix for conventional vehicles. Figure 3.1 shows the flow of energy for the most prominent technologies in the light duty vehicle transportation system, as well as technologies previously discussed in this thesis. For simplicity in the structure of the study, only gasoline internal combustions engine vehicles (ICEV) running on gasoline-ethanol blends up to E10, flex fuel ICEV running on blends up to E85, and electric vehicles (EV) operating entirely on electricity are considered. The construction of the model and key assumptions are described in this section. The complete STELLA® model, as well as depictions of graphical assumptions can be seen in Appendix A and Appendix B.

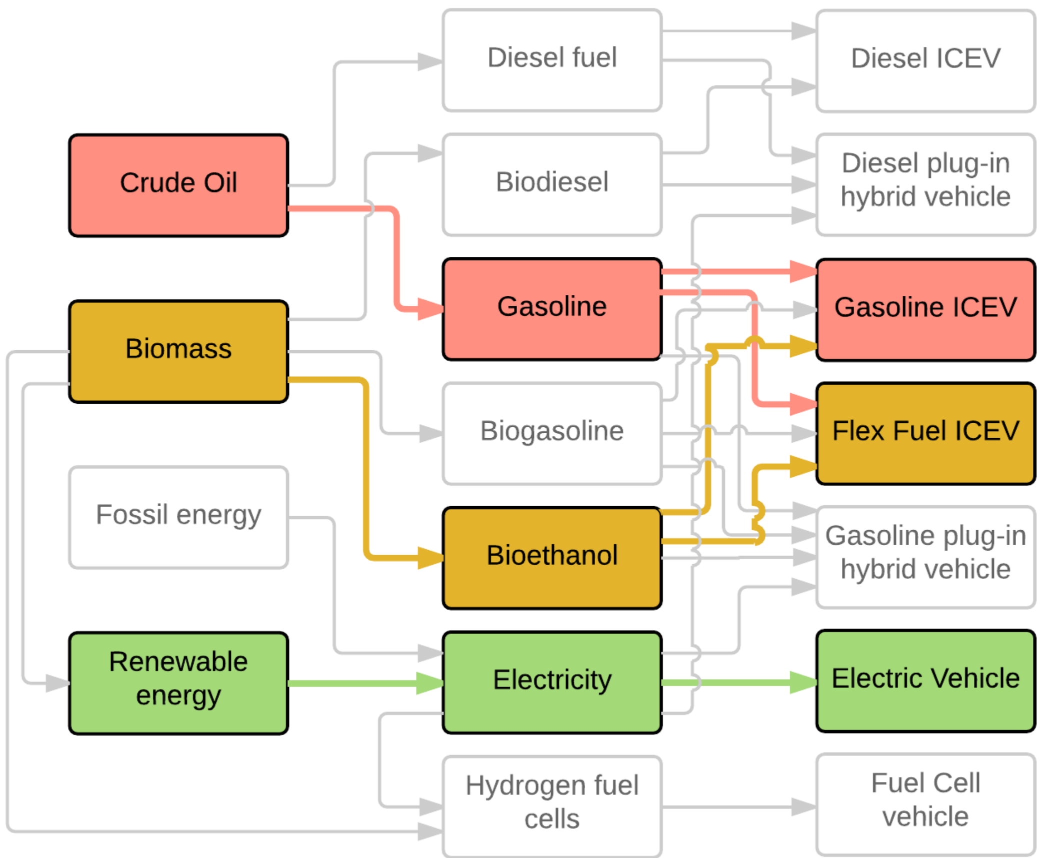


Figure 3.1 Flow of energy through the light duty vehicle system. Areas of significance to this study are highlighted in colour.

3.1 Overall system

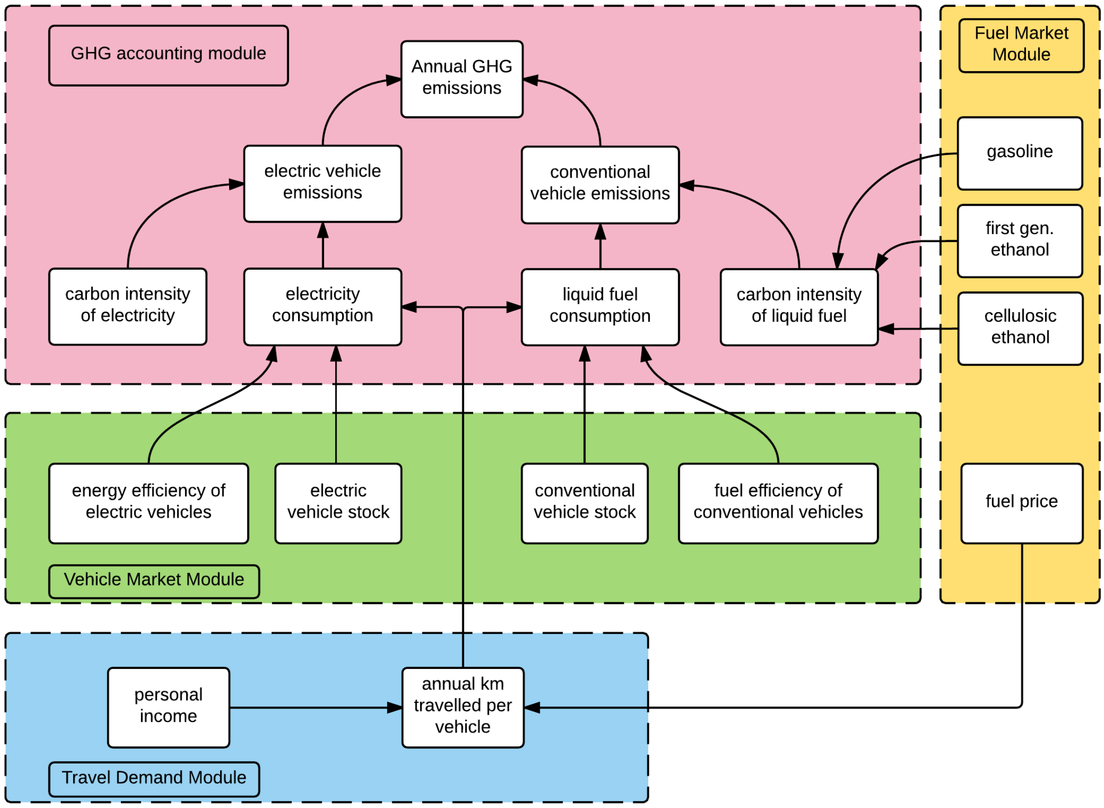


Figure 3.2 Simplified flowchart of GHG emissions from EVs and conventional vehicles through the modules in the system.

Figure 3.2 shows the basic flow of GHG emissions in our assumed light duty vehicle system. In the STELLA® model, the annual GHG emissions are determined in the *GHG accounting* module by the total energy or fuel use from each type of vehicle and the carbon intensity of that energy or fuel. The numbers of EVs and conventional vehicles added to and removed from the road each year is determined in the *vehicle market* module, as is the fuel efficiency of each vehicle type. Annual *travel demand* per vehicle is determined in its own module and is dependent on the price of fuel and personal income. A *fuel market* module determines the price of fuel, and the composition of the liquid fuel mix.

The computer model uses the Euler integration method with a time step of 0.1 years for its simulations. The time frame for all simulations is 50 years, from 2000 to 2050, and all units of time are measured in years. Years 2000 to 2013 were used to verify the model against the latest historic figures for GHG emissions from light duty vehicle travel in British Columbia, while years 2014 to 2050 are used to project long-term impacts of various policy scenarios.

The remainder of this chapter describes each module and its construction using systems analysis, system dynamics, and STELLA® computer modelling software.

3.2 Causal loop diagrams

The following sections utilize causal loop diagrams to emphasize the feedback loops inherent in dynamic systems. An arrow from entity X to entity Y with a '+' sign at the arrowhead indicates a positive causal relationship (i.e. a change in value of X causes a change in Y in the same direction). An arrow with a '-' sign at the head indicates a negative causal relationship (i.e. a change in X leads to a change in Y in the opposite direction). A bold symbol **B** represents a balancing loop, or a negative feedback loop. These balancing loops stabilize over time to reach equilibrium. A bold **R** represents a reinforcing, or positive feedback loop. In a reinforcing loop, given a change in one entity, the effect is amplified as it travels through the loop—a change in value of one entity eventually causing a change in value in the same direction in the same entity. Understanding these causal relationships can aid in simulating and understanding the behaviour of a system.

3.3 Electric vehicles in the vehicle market module

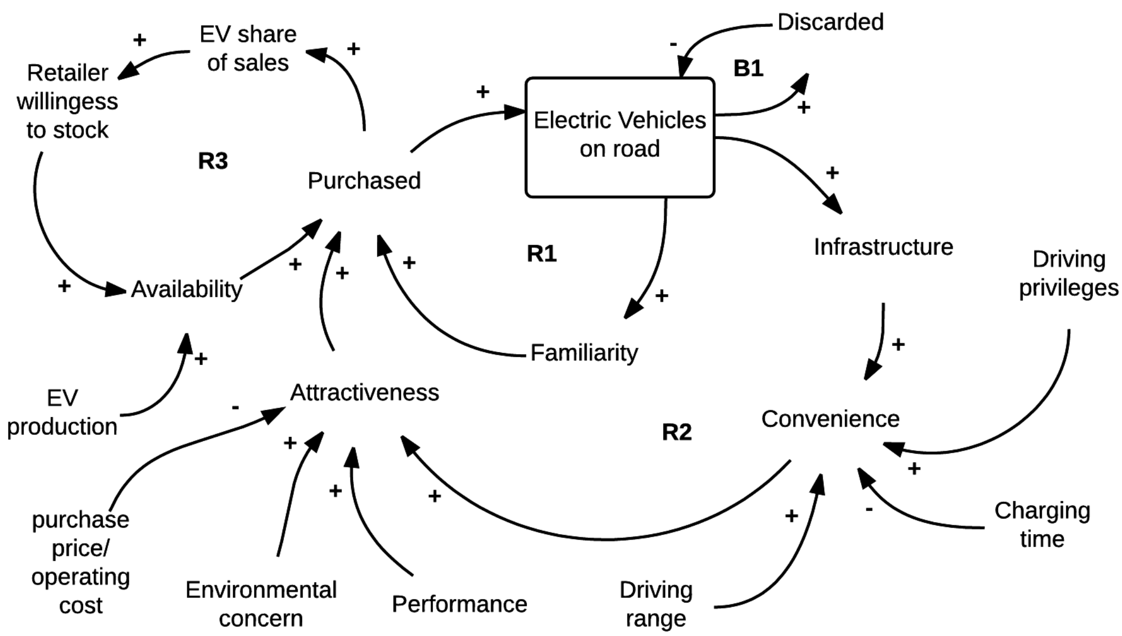


Figure 3.3 Causal loop diagram of electric vehicle demand and sales in the vehicle market.

The causal loop diagram in figure 3.3 draws inspiration from Struben and Sterman (2008) and shows three reinforcing loops affecting the purchase and resulting stock of electric vehicles in the system. The reinforcing loop **R1** describes a consumer's likelihood to purchase an EV based on their level of familiarity with the product. The more EVs there are on the road, the more familiar the consumer becomes with the technology, and the more likely they are to consider it as a viable purchase. However, if there are few electric vehicles on the road, fewer consumers will be familiar with the technology, resulting in fewer potential sales. **R2** depicts EV attractiveness according to convenience. If there are more EV on the road, there is likely to be greater investment in infrastructure (e.g. fast-charging stations), which increases the convenience of driving and owning an EV, boosting attractiveness and thus sales. Convenience is also influenced by the driving range on a full battery charge, and the time it takes to achieve a full charge relative to a conventional vehicle being refuelled. Furthermore, adding special driving privileges for EV users, such as bus lane access or free parking can boost convenience relative to conventional vehicles. **R3** represents the supply side of the EV system. Increased sales increase a retailer's willingness to stock EVs, adding to the availability and variety of EVs and increasing the potential for sales. However, the amount of product that a retailer can stock is dependent on EV production outside the province. The balancing loop, **B1**, describes the removal of EV from the stock at the end of their on-road lifetime. This is not assumed to play a significant factor in the adoption of EVs.

Price, performance, and environmental concern are assumed to be exogenous variables that affect the attractiveness of EVs. Performance (e.g. comfort, style, top speed) is assumed to increase over time due to technological improvements outside the system boundary of the vehicle market place in British Columbia. Price of EVs, which is mainly influenced by battery costs (Nykvist & Nilsson, 2015), is also assumed to be tied to technological advancements outside of the system examined here. Environmental concern in vehicle choice, we assume to increase exogenously over time as public awareness of CO_2 emissions and their impact on the environment increases.

What follows is a description of the modelled vehicle market and according assumptions based on the above causal loop diagram. An image of the vehicle market module in the overall computer model can be viewed in Appendix A.

3.3.1 Determining EV demand

To simulate the market penetration of electric vehicles in British Columbia over the years 2000 to 2050, the total on-road vehicles were separated into two main stocks: *EV on-road stock* and *CV on-road stock,* where CV is a conventional vehicle. Vehicles are added to the on-road stocks as they are purchased new, and removed at the end of their lifetime. Once a vehicle is removed from an on-road stock, it is directly converted (1:1) into vehicle demand, which is then directly translated into a new vehicle purchase. In other words, new vehicles simultaneously replace old ones as they are removed from the total stock. Used vehicle sales are not counted in the model, as it is assumed that once a car enters the on-road stock, it will remain there until it reaches the end of its lifetime. Over the lifetime of a vehicle, it may have one, or many owners, but this assumed to be unimportant to the outcome of the simulation.

On top of demand from removed vehicles, total vehicle demand is also assumed to grow exogenously. Historical vehicle population growth rates up to 2014 were calculated from public vehicle registration records (Statistics Canada, 2014), and applied to the total vehicle stock in the model (see Appendix B for growth rate). After 2014, the vehicle population is assumed to grow at 0.62 times the rate of per-capita income growth (Dargay et al., 2007). Projected GDP per capita in British Columbia (NEB, 2016) is used as a proxy for income for the simulation to 2050.

All growth of the overall vehicle stock is assumed to come from new vehicle purchases. (Certainly, some vehicle growth may be a result of importing used vehicles into the province but this is considered outside the scope of this study). Furthermore, new vehicle supply is assumed to always be able to meet demand, and purchased new vehicles are assumed to stay on the road over their entire lifetime. By varying the assumed lifetime of vehicles in the model, and comparing the simulated new vehicle demand with historic new vehicle sales between 2000 and 2015 (Statistics Canada, 2016a), a vehicle lifetime of 16 years was determined as it most closely reproduces the historical data.

Once the total vehicle demand in each year is determined, it is translated into sales of each vehicle type according to their respective demands. We assume that the consumer is presented with a choice between only an EV and a conventional vehicle. Competition between other alternative fuel vehicles and electric vehicles is not considered. In that respect, demand for EVs is determined relative to a conventional vehicle, and its share of the demand is assumed to be the weighted mean of five demand factors, each expressed as a value between 0 and 1 and each calculated relative to a conventional vehicle. The following equation expresses EVs share of the overall demand in each year:

$$EV\ share\ of\ demand = \frac{2 * d_{ec} + d_{soc} + d_{env} + k + p}{6} \tag{1}$$

where d_{ec} is economic demand, d_{soc} is social demand, d_{env} is environmental demand, k is convenience, and p is performance.

3.3.2 Economic demand

Economic demand is given twice the weight of the other demand factors as, based on the literature reviewed earlier, it is generally the most highly weighted factor in the decision to purchase an electric vehicle (Bjerkan et al., 2016). We determine the economic demand relative to the lifetime cost of owning a conventional vehicle in terms of purchase price and operating costs. Also, since purchase price is given higher value than operating costs in most consumer studies (Allcott & Wozny, 2014; Rezvani et al., 2015), we assign purchase price twice the weight of operating cost when calculating the lifetime cost of vehicle ownership in order to represent a high case of economic short-sightedness in vehicle purchase decisions. The perceived lifetime cost of owning either an EV or conventional vehicle is then calculated as:

$$C_{lifetime} = 2 * P + C_{operating} \tag{2}$$

where $C_{lifetime}$ is the lifetime cost, P is purchase price, and $C_{operating}$ is the operating cost over the lifetime of the vehicle.

Given the 2016 purchase price of the Nissan Leaf, and the equivalently sized Honda Civic (recall table 2.1), we assume that an EV comes at 1.8 times the purchase price of an equivalent conventional vehicle in 2016, and that this decreases linearly to 1.2 times the price in 2050 due to lower costs of battery production in the future (Nykvist & Nilsson, 2015). Also a 7% provincial sales tax, and a 5% federal tax are added to the purchase price, with an option to exempt the 7% sales tax for EV purchases.

Operating costs for EVs and conventional vehicles are restricted to the annual fuel/electricity costs plus a one-time battery replacement cost for EVs. Further expenses, such as road fees, taxes, insurance, and maintenance are not considered. The same vehicle kilometers travelled (VKT) are assumed for both EV and conventional vehicles (determined in the *travel demand* module), and then energy prices (NEB, 2016) and energy efficiency (exogenous for EV, endogenous for CV) are used to calculate the annual energy costs for operating each vehicle. All of the annual operating costs over the lifetime of each vehicle are then converted into a net present value, assuming a lifetime of 16 years for each vehicle and an annual discount rate of 5% (Driscoll et al., 2013). Furthermore, the EV battery replacement cost is assumed to decrease from $12,000 at the onset of the simulation, to $6,000 in 2050, passing through $9140 for an EV purchased in 2016, which is based on an estimate of future subsidized battery costs of around $300/kWh (Matteson & Williams, 2015). Learning-by-doing we assume causes the battery replacement cost to decrease gradually to $6000 in 2050 and the battery is assumed be replaced after 8 years on the road. 8 years was chosen as it represents half of the vehicle's assumed lifetime. However, battery replacement depends heavily on the individual driver's habits and expectations (Saxena et al., 2015) which are outside the scope of this model. The future battery cost is converted to present value costs for EV operation using the same annual discount rate mentioned above. Since a lower lifetime cost implies higher economic demand, we calculate economic demand for an EV relative to a conventional vehicle by the following equation:

$$d_{ec} = \frac{C_{lifetime,CV}}{C_{lifetime,EV} + C_{lifetime,CV}} \tag{3}$$

where d_{ec} is economic demand and $C_{lifetime}$ is the lifetime cost of ownership of vehicle type EV or CV. Thus the economic demand for an electric vehicle is equal to the lifetime cost of a conventional vehicle, divided by the sum of the lifetime costs of an electric vehicle and a conventional vehicle.

3.3.3 Social demand

Social demand is determined relative to the market penetration of EVs—or its share of the on-road stock. The "neighbour effect" (Axsen et al., 2009; Mau et al., 2008) describes the increased preference for a product as its degree of market penetration increases. We simulate the social demand in this model according to the neighbour effect—and S-shaped curve going from 0 to 1 as EV's share of the vehicle stock goes from 0 to 1 (Appendix B).

3.3.4 Environmental demand

Environmental demand is generated by the following function:

$$d_{env} = c_{env} * \frac{e_{CV}}{e_{EV} + e_{CV}} \tag{4}$$

where d_{env} is the environmental demand, c_{env} is environmental concern—an assumed S-shaped curve increasing exogenously over time due to education and awareness (see Appendix B)—and e is the average emissions per km of driving a given vehicle type (EV or CV). Since the EV stock is assumed to be composed entirely of fully electric vehicles powered by the British Columbia electricity grid, their emissions are determined by average EV energy consumption per km and the carbon intensity of electricity generation in the province. EV energy consumption per km is assumed to decrease over time from 0.20 kWh/km (EPA, n.d.) to 0.148 kWh/km in 2050 due to exogenous technological advances in efficiency (Appendix B), while the carbon intensity of electricity generation is assumed to stay constant (NEB, 2016). Conventional vehicle emissions are the product of average fuel consumption per km and the carbon intensity of the liquid fuel mix supplied by retailers (these variables are determined in the *fuel market* module, and are discussed in more detail later).

3.3.5 Convenience

EV convenience is assumed to be the mean demand values of charging infrastructure, charging time, driving range, and special driving privileges, compared to a conventional vehicle. It is expressed by the following:

$$k = \frac{I + R + Ch + Pr}{4} \tag{5}$$

where k is EV convenience, I is infrastructure, R is range, Ch is charging time, and Pr is special driving privileges. Due to demand from added EVs, infrastructure (namely charging stations) is assumed to increase at 3/4 the rate that EV's share of the vehicle stock increases. Charging access can be divided into home access and public access. We assume that the purchase of an EV corresponds almost perfectly to home charging access (Axsen et al., 2015). If all charging for EVs was to occur at home, then EV share of stock and charging infrastructure would directly correlate to one another since all new EV would be met with necessary charging infrastructure as they are purchased. However if we assume that public charging will inevitably be necessary due to any number of factors, but with less necessity than home access, then we can assign a lesser weight (in terms of convenience) to public charging access. As we cannot expect public charging infrastructure to meet added EV stock perfectly (even under the most optimistic conditions) then charging infrastructure must be below the EV share of stock. Thus by setting infrastructure to 3/4 of the EV share of stock, we assume that most charging demand is met through home access while accounting for shortcomings in public charging access. Driving range on a full battery charge is based on the current reported range of 172 km for a 2016 Nissan Leaf (Nissan, n.d.) and is assumed to increase linearly to half the range of an equivalent conventional vehicle by 2050. Charging time (the time it takes for a completely depleted battery to fully recharge) is based on recently reported charging times for a 30 kWh battery using a 240v level 2 charger and is assumed to improve gradually from 4 hours in 2015 (Nissan, n.d.), to under 3 hours in 2050 due technology improvements and increased access to very fast chargers. We assume that a charging time of 30 minutes or less would result in equal refuelling convenience to a gasoline vehicle. Special driving privileges are by default assumed to be the same as those offered to conventional vehicles. In the model's interface layer, the user can scale up or down the driving privileges of an EV compared to a conventional vehicle.

3.3.6 Performance

For performance demand, we consider factors not already accounted for in the convenience factor, such as top speed and comfort. We assume that EV performance will increase linearly from ½ the performance relative to conventional vehicle in 2015, to equal that of conventional vehicles by 2040 and thereafter due to exogenous technology improvements (curve shown in Appendix B).

Additionally, between 2000 and 2011 in the simulation, EV demand is held to 0.1%. We assume that EV demand only begins at the onset of British Columbia's EV initiatives in 2011. So endogenous demand is introduced to the model in 2011, and is assumed to be phased in over 4 years (Appendix B), so that by 2015 the full demand potential is measured. However, EV demand only translates into vehicle purchases after being subject to the constraints described next.

3.3.7 Constraints to EV market penetration

We assume two main constraints to EV adoption as discussed by Axsen et al. (2015): lack of familiarity with EVs and lack of availability of EVs. In the model, we represent each constraint as a value between 0 (no familiarity/availability) and 1 (complete familiarity/availability). The constrained EV demand is determined by multiplying the EV share of demand by each of the familiarity and availability constraints. The market share of EV, or the share of demand that is translated into actual sales is represented as:

$$EV\ Market\ share = (EV\ share\ of\ demand) * K_f * K_a \tag{6}$$

where K_f is the familiarity constraint, and K_a is the availability constraint. The demand side constraint, familiarity, assumes that despite economic, performance, or convenience based demand for an EV relative to a conventional vehicle, the demand for EV will not be realized unless a sufficient number of consumers are familiar with or aware of EVs and how they function. Based on a survey of recent vehicle buyers in BC, Axsen et al. (2015) found that 14% of respondents claimed to be 'familiar' with an EV (the Nissan Leaf was used as an example). In our model we assume that familiarity is determined by the share of EVs on the road. We assume that once EVs make up 25% of the on-road stock, 100% of consumers will be familiar with the vehicle. Thus we assume familiarity to increase linearly from 0.14 to 1 as EV's share of the vehicle stock goes from 0 to 0.25.

Availability is a supply side constraint. If there are not enough vehicles available, nor a wide enough variety to choose from, full demand potential cannot be realized. First, we assume that EV supply will always be able to keep up with demand. Thus in our simulation, availability of EVs is reliant only on the variety of models in the market and the number of those that are stocked by a retailer. We assume eight different EVs are on the market today (Canadian Automobile Association, 2016), increasing stepwise by at most 1 model per year until 20 different EV models are on the market in 2030 and thereafter. At this point, we assume based on the study by Axsen et al. (2015), that EV options will be available in each of the four categories: compact, sedan, midsize SUV, and full size SUV. It is further assumed that an auto dealer's willingness to stock EV models depends on their share of sales—willingness to stock EVs increasing linearly from 0 to 1 as EV share of sales increases from 0 to 0.5 (i.e. dealers will want to stock all EV models once their sales reach 50% of the market share). An initial variety of 2 EVs is assigned to the dealership in order to ensure EVs are available for purchase from the onset of the simulation. Finally, it is assumed that there will be no availability constraint to EV adoption once there are 20 varieties of EV widely available, so the *availability* constraint variable takes the value of the number of different EV stocked by a dealer divided by 20.

As EV's market share of the demand is calculated relative to conventional vehicles, then the share of demand for conventional vehicles is expressed as '*1 – EV market share*'. Thus the respective shares for EVs and conventional vehicles sum to one and account for the entirety of the vehicle demand in the province.

3.4 Fuel efficiency of conventional vehicles

Once the demand for conventional vehicle purchases is determined, a distinction is made as to which type of conventional vehicle is purchased. To minimize complexity in the model, the total conventional vehicle stock was separated into just two categories, low fuel-efficiency and high fuel-efficiency, based on fuel consumption in litres of gasoline equivalent per 100 km of driving (Lge/100km). Low efficiency light duty vehicles are considered to be light trucks, vans, SUVs, and heavier passenger vehicles that exhibit worse than the average fuel efficiency of vehicles in the simulation. We assume that the average new low-efficiency vehicle achieves 12.0 Lge/100km in the year 2000 and improves linearly to 7.1 Lge/100km by 2025 due to technological advances and government mandates (EPA, 2010/2012). After 2025, only a minor improvement to 6.0 Lge/100km by 2050 is assumed (see Appendix B). These figures up to 2025 are based on the U.S.'s Corporate Average Fuel Economy (CAFE) standards, which mandate average efficiency standards for different vehicle types in a given year. For low fuel-efficiency vehicles we chose the CAFE standard for 'light trucks' (EPA, 2010/2012).

High efficiency vehicles are assumed to be lightweight, small passenger vehicles including hybrid-electric gasoline vehicles and full gasoline vehicles, with better than average fuel efficiency. We assume these vehicles achieve fuel efficiency set out by the CAFE standards for a 'compact car' (EPA, 2010/2012). From 2000 to 2025, according to the CAFE standard, we assume a fuel efficiency that improves from 8.0 to 3.8 Lge/100km, and from 2025 to 2050, a small improvement to 3.0 Lge/100km (Appendix B).

The CAFE standards for average fuel efficiency were chosen to represent the progression of new conventional light duty vehicles, as the government of Canada has issued legislation to enact standards in line with the U.S. CAFE standards (Government of Canada, 2014).

Figure 3.4 shows a simplified causal loop diagram of the feedback caused by changes in the average fuel efficiency of the vehicle stock. By aggregating the fuel efficiency over the entire conventional vehicle stock, we assume that the system behaves according to the average costs of driving over the entire fleet. Any increase in fuel costs per km, whether caused by an increase in the price of fuel or a decrease in efficiency, leads to increased demand for fuel efficiency, causing an increased share of high-efficiency vehicle purchases. When added to the conventional vehicle stock, the high-efficiency vehicles improve the average efficiency of the stock, thus decreasing the fuel cost per km (balancing loop **B1** in figure 3.4). A decrease in fuel costs per km lowers the demand for fuel efficiency, leading to a greater share of low-efficiency vehicle purchases, which lowers the average fuel-efficiency of the vehicle stock and raises the average fuel cost per km (balancing loop **B2** in figure 3.4). The resulting fuel efficiency of the conventional vehicle stock is an equilibrium, shifted up or down by changes to the cost of driving.

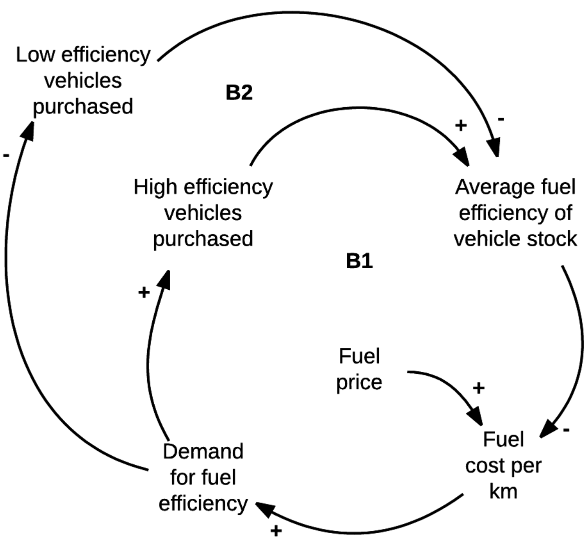


Figure 3.4 Simplified causal loop diagram of fuel efficiency of vehicles in the conventional vehicle stock.

Low- and high-efficiency vehicles are purchased according to their respective share of the conventional vehicle demand. Overall demand for conventional vehicles is already determined in the *vehicle market* module, but the share of purchases allotted to each type of conventional vehicle is determined in this subsystem. In the year 2000, at the onset of our simulation, we assume that high-efficiency and low-efficiency vehicles have equal consumer demand. As time progresses in the simulation, demand for high-efficiency vehicles in year *t* is given by the following formula:

$$H_t = H_{t-1} * \frac{Ckm_t - Ckm_{t-1}}{Ckm_{t-1}} * \alpha \tag{7}$$

where H_t is share of demand for high-efficiency vehicles in year *t*, Ckm_t is the cost per km of driving in year *t*, and α is the travel cost elasticity. The fractional term in equation (7) represents the percent change in the cost per km of driving from the previous year to the current year. The cost per km of driving is the product of the litre price of gasoline and the average overall fuel efficiency per km of the conventional vehicle stock. A travel cost elasticity, $\alpha = 0.48$, was determined heuristically and applied to the demand in order to more closely fit the historic data for fuel efficiency in light duty vehicles and annual GHG emissions from vehicle use (BC Provincial Government, 2014; Natural Resources Canada, 2011).

Since we assume that high efficiency vehicles have 50% of the conventional vehicle demand at the onset of the simulation, then the average factory efficiency rating for conventional vehicles is assumed to be 10.0 Lge/100km for the entire stock (the mean of 12 Lge/100km and 8 Lge/100km for low- and high-efficiency vehicles respectively).

As they are purchased new, each type of conventional vehicle (either low or high efficiency) is added to a conveyor with a transition time of 1 year. At the end of the year, the vehicle is no longer considered ‘new,’ but remains in the on-road stock for the duration of its lifetime, and its fuel efficiency rating continues to be counted towards the overall fleet average. In a given year, the share of sales for each of low or high efficiency conventional vehicle determines the average fuel efficiency of vehicles added to the total stock in that year. Since the efficiency of new vehicles purchased can vary from year to year, we track the average fuel efficiency and total number of all conventional vehicles purchased in a given year over a 16 year period—or the time it takes to completely turn over the stock. Yearly conventional vehicle sales numbers and average efficiency are stored in a series of 16 converters using a 'delay' function that reports back the given sales volume and fuel efficiency values over the range of *t-15* to *t*. The overall average fuel efficiency for the conventional vehicle stock is then calculated as the weighted mean of these 16 converters (weighted according to the volume of sales in the year).

At the start of the simulation, we assume that all on-road conventional vehicles have the same fuel efficiency. Thus, when $t < 16$, the average efficiency is calculated from that of all new vehicles on the road (purchased between $t=0$ and $t=15$) along with all that remain from the initial stock at $t=0$. From $t = 16$ onward, the sum of the new vehicles added each year from *t-15* to *t* is equal to the total conventional vehicle stock and thus the average fuel efficiency of the overall conventional vehicle stock is the mean efficiency of all new vehicles added to the road over the previous 16 years.

The fuel efficiency ratings assumed for the vehicles, as those in the CAFE standards, represent factory ratings under controlled conditions. In order to adjust for loss of efficiency due to real world driving conditions, we assumed an efficiency loss of 20% for all vehicles (Melaina & Webster, 2011) and applied that to the fuel efficiency ratings in the simulation when calculating real world fuel demand.

Furthermore, it is assumed that there will be no impediment to automobile manufacturers in meeting the mandated efficiency standards in each model year. We also assume that the manufacturers meet the standards for gasoline internal combustion engine vehicles using conventional and non plug-in hybrid technology. This allows the model to track electricity use from the vehicle stock purely within the EV stock. Assessing the ability of manufacturers to meet CAFE-style efficiency standards is beyond the scope of this study. The increasing efficiency standards assumed here serve mainly as a virtual guide for the progression of conventional vehicles, while we focus our attention on the liquid fuels that power them, and the electric vehicles with which conventional vehicles compete for sales.

3.5 Travel demand module

In each year, the vehicle travel demand is assumed to change relative to changes in personal income and changes in retail fuel prices. The annual travel demand per vehicle is determined by the following formula:

$$T_t = T_{t-1} * \left(\frac{Y_t - Y_{t-1}}{Y_{t-1}} * \beta + \frac{L_t - L_{t-1}}{L_{t-1}} * \gamma \right) \tag{8}$$

where T_t is the annual travel demand (in km) per vehicle in year t, Y_t is per capita income in year t, β is income elasticity, L_t is the price per litre of fuel in year t, and γ is fuel price elasticity. Each fractional term in equation (8) represents the per cent change in income or fuel price from the previous year to the current year. Income and fuel price elasticities, $\beta = 0.70$ and $\gamma = -0.48$ respectively, were taken from literature (Dahl, 2012), however the income elasticity was adjusted heuristically from 0.72 to 0.70 to more closely fit historic values for travel demand in British Columbia (Natural Resources Canada, 2011). Per capita GDP projections to the year 2040 were used as a proxy for income, and gas prices to 2040 were assumed from reference case from the National Energy Board of Canada's energy projections to 2040 (NEB, 2016). Since projections were only available to 2040, the model assumes that income and gasoline prices will follow the same trajectory from 2040 to 2050 as they did from 2030 to 2040. An initial value for average light duty vehicle travel demand at the onset of the simulation was taken from the Canadian Vehicle Survey and set to 14,975 km (Natural Resources Canada, 2011).

3.6 Fuel market module

3.6.1 Flex fuel vehicles and ethanol availability

We assume that by 2020 and thereafter, flex-fuel vehicles (FFVs) (those that can run on a combination of gasoline and ethanol up to E85) will make up 96% of all new conventional vehicle sales. This has already been observed in Brazil where flex fuel vehicle sales accounted for almost 100% of the market share in 2006 (Ferreira et al., 2009). By leaving 4% of new vehicles in each year after 2020 non-flex-fuel, we assume to account for exceptions to the market penetration of flex-fuel engines. Consumer access to higher ethanol-gasoline blends is assumed to be limited by the share of filling stations equipped with blender-pumps that allow the retailer to sell the regular gasoline-class fuel mix or blends up to E85 out of the same pump. We assume the number of gasoline filling stations in British Columbia is constant at 2,134 stations (Statistics Canada, 2014) although this number could be subject to change depending on future fuel demands. The user in the model's interface layer controls the installation rate of blender pumps, and it is assumed that all flex fuel vehicles will have access to higher ethanol blends once 50% of the total gas stations in British Columbia have installed blending technology. The share of conventional vehicles compatible with E85 and with access to E85 is then determined by the following equation:

$$V_{E85} = V_{FFV} * \frac{S_{E85}}{0.5 * S_{total}} \tag{9}$$

where V_{E85} is the share of conventional vehicles compatible with and with access to E85 fuel, V_{FFV} is the share of conventional vehicles that have flex fuel engines, S_{E85} is the number of gas stations carrying E85, and S_{total} is the total number of gas stations in British Columbia. It is also assumed that the E85 availability component (the fractional term in equation (9)) must not exceed 1. Thus when the number of gas stations carrying E85 exceeds half the total number of gas stations, the fractional term is 1 and all flex fuel vehicles will have access to E85.

3.6.2 Ethanol's share of the liquid fuel mix

It is assumed that all flex fuel vehicle drivers with access to E85 will choose it over the regular low ethanol-gasoline blend mandated by British Columbia's renewable fuel regulation. This is a lofty assumption—and one that would likely require significant policy intervention—as it denies the concept of path dependence, or choosing the regular gasoline blend over the high ethanol blend because that is what the consumer is familiar with using. However, for the scope of this study, and in order to explore higher levels of ethanol consumption without consumer resistance, we assume that E85 will be chosen when the choice is available. The share of ethanol in the total annual gasoline-class fuel sales for conventional vehicles is then calculated by the following equation:

$$F_{eth} = V_{E85} * 0.85 + (1 - V_{E85}) * F_{min} \tag{10}$$

where F_{eth} is the share of ethanol in the annual gasoline-class fuel sales, V_{E85} is the share of conventional vehicles compatible with and with access to E85 determined in equation (9), 0.85 is the concentration of ethanol in E85, $(1 - V_{E85})$ is the share of conventional vehicles **not** refuelling with E85, and F_{min} is the minimum concentration of ethanol in the gasoline-class fuel mix as mandated by the provincial government.

3.6.3 Total gasoline-class fuel demand

The total gasoline-class fuel demand in a year is a function of the total distance travelled by all conventional vehicles and the average fuel efficiency of the conventional vehicle stock. However, recall that since ethanol has a lower energy density than gasoline, higher concentrations of ethanol in the gasoline-class fuel mix causes lower fuel efficiency (by volume) in vehicles. Thus we must account for the concentration of ethanol in the fuel mix when calculating the annual fuel demand. The demand is then determined by the following equation:

$$Total\ annual\ fuel\ demand = D_{CV} * M * \delta \tag{11}$$

where D_{CV} is the total distance travelled by all conventional vehicles in a year, M is the average fuel efficiency of the conventional vehicle stock, and δ adjusts the fuel efficiency of conventional vehicles for the energy density of the fuel mix as a result of its ethanol concentration. We calculate δ by the following:

$$\delta = \frac{ED_{gasoline}}{ED_{fuelmix}} \tag{12}$$

where $ED_{gasoline}$ is the energy density of gasoline, and $ED_{fuelmix}$ is the average energy density of the gasoline-ethanol liquid fuel mix used by the conventional vehicle stock. Energy density of the fuel mix is determined by:

$$ED_{fuelmix} = ED_{eth} * F_{eth} + ED_{gasoline} * (1 - F_{eth}) \tag{13}$$

where ED_{eth} is the energy density of ethanol, F_{eth} is the share of ethanol in the fuel mix, $ED_{gasoline}$ is the energy density of gasoline, and $(1 - F_{eth})$ is the share of gasoline in the fuel mix. (The energy densities of gasoline and ethanol, as well as other properties are discussed in the following section 3.7).

Total volume of ethanol demand in a year is then represented by the following equation:

$$Annual\ ethanol\ demand = (Total\ annual\ fuel\ demand) * F_{eth} \tag{14}$$

where total fuel demand is determined in equation (11), and F_{eth} is the share of ethanol in the annual gasoline-class fuel sales as determined in equation (10).

Annual gasoline demand is simply the difference between the total annual fuel demand and the demand for ethanol.

3.6.4 Ethanol resources

At the onset of the simulation, all ethanol demand is met by imported ethanol (either from out of province, or from outside the country). After 2015, the model allows the user to explore development of domestic ethanol production within British Columbia. The demand for the number of ethanol plants in British Columbia is determined by the total volume of ethanol consumed, divided by the production capacity of a cellulosic bioethanol plant—assumed to be 200 million L/year (Mabee et al., 2011). Incremental bioethanol plant demand is then converted to plant construction up to a maximum number of plants set by the user. Plant construction time is assumed to be 5 years, at the end of which, full plant production capacity may be achieved. The resulting shares of bioethanol supplied domestically and imported are tracked and used in the *GHG accounting* module to determine the carbon intensity of the provincial ethanol supply.

3.7 Greenhouse gas accounting module

As discussed in chapter 2, for their inventory reports, the British Columbia Provincial Government reports tank-to-wheel GHG emissions from transportation fuels. In this respect, the GHG emissions resulting from consumption of transportation fuels are counted as the amount of CO_2e released upon combustion. By also considering the well-to-wheel, or lifetime emissions, one can examine the emissions resulting from all stages of the fuel's life and not just the use phase, providing a more robust perspective on the impact of a fuel's consumption. For imported gasoline and ethanol, the well-to-tank portion (e.g. production and transportation) of the fuels' lifetimes occur outside of the provincial border and do not directly lead to emissions in British Columbia. However, by counting well-to-wheel emissions in the modelled simulations, we include imported well-to-tank emissions towards British Columbia's annual GHG emissions in order to place onus on the province for the full lifetime impact of the fuels consumed within its borders.

Although it would also be useful to consider the emissions embodied in production and end-of-life phases of the vehicles themselves, it is outside the scope of this study. Thus we limit our analysis to the lifetime GHG emissions from transportation fuels only.

3.7.1 Properties of transportation fuels

Properties for the transportation fuels considered in this study are summarized in table 3.1. The National Energy Board forecasts that between 2011 and 2040, renewables—mainly hydroelectric generation—will continue to account for 96-99% of the total electricity generation in the province (NEB, 2016), thus over the course of the simulation, the model assumes a constant carbon intensity for electricity generation of 10.0 g CO_2e/kWh based on 2011 levels (BC Ministry of Environment, 2014a). Thus the annual GHG emissions from EV travel depends on the total electricity required to power the entire fleet and the carbon intensity of the electricity generation.

Since the liquid fuel mix for the conventional vehicle stock is a combination of two fuels—ethanol and gasoline—with different properties, certain distinctions must be made. First, the energy density of ethanol is lower than that of gasoline, thus the energy density of the overall fuel mix depends on the share of ethanol present, as was shown in equation (13). We assume ethanol to have an energy density of 23.58 MJ/L, while gasoline contains 34.69 MJ/L (BC Ministry of Energy and Mines, 2014).

Table 3.1 Assumed well-to-wheel carbon intensities and energy densities for transportation fuels within the scope of this study.

Fuel type	**Carbon intensity** (g CO_2e/MJ)	**Energy density** (MJ/L)	**Reference**
Gasoline (includes ethanol) pre-2012	87.29	34.69	British Columbia (2008)
Gasoline 2012-2050	90.21	34.69	BC Ministry of Energy and Mines (2014); British Columbia (2008)
First generation ethanol	53.11	23.58	BC Ministry of Energy and Mines (2014); British Columbia (2008)
Cellulosic ethanol (forest)	14.05	23.58	Karlsson et al. (2014)
Electricity	2.78 (10.0 gCO_2e/kWh)	N/A	BC Ministry of Environment (2014a)

As stated previously, not only do gasoline and ethanol have different lifetime carbon intensities, but the intensities also vary depending on how each fuel was produced. Up to 2011 we assume an average carbon intensity of gasoline class fuel including ethanol to be 87.29 g CO_2e/MJ as that is the default intensity based on British Columbia's reporting standards (British Columbia, 2008). However, starting in 2012, retailers were required to report the average carbon intensity for each fuel type they stocked (BC Ministry of Energy and Mines, 2014). To date, only the 2012 figures are available, with retailers reporting an average lifetime carbon intensity of 90.21 g CO_2e/MJ for gasoline, and 53.11 g CO_2e/MJ for ethanol (BC Ministry of Energy and Mines, 2014). So, from 2000 to 2011 in the simulation we assume a carbon intensity for the gasoline class fuel of 87.29 g CO_2e/MJ, and from 2012 onwards we use the latest available figures, 90.21 g CO_2e/MJ for gasoline and 53.11 g CO_2e/MJ for first generation ethanol, and the overall carbon intensity relies on the concentrations of each fuel type in the gasoline mix. As a result of this assumption, a minor jump in carbon intensity of the fuel mix in 2012 is observed in the simulation when the carbon intensity of the fuel mix switches from the default value to the simulated value. Cellulosic ethanol produced from forestry residues, which is introduced for future scenarios in the model, we assume to have a carbon intensity of 14.05 g CO_2e/MJ based on the average of two lifecycle assessments conducted by Karlsson et al. (2014).

The overall carbon intensity of the fuel mix for conventional vehicles then depends on the share of each of the three fuel types in one unit of energy. When calculating the carbon intensity of the ethanol in the fuel mix we consider the share of imported ethanol and the share produced in British Columbia using the following equation:

$$I_{eth} = (imported\ share) * I_{eth1} + (domestic\ share) * I_{eth2} \tag{15}$$

where I_{eth} is the carbon intensity of the ethanol consumed by conventional vehicles, *imported share* is the share of the total volume of ethanol supplied from out of province, I_{eth1} is the carbon intensity of first generation ethanol, *domestic share* is the share of the total volume of ethanol supplied by domestically produced cellulosic ethanol, and I_{eth2} is the carbon intensity of second-generation cellulosic ethanol. Imported and domestic shares of ethanol in the total ethanol pool depend on the ethanol demand from vehicles and the ability of ethanol production from BC forestry residues to meet the demand. All ethanol demand not met by local production is assumed to be met with imported product. (Domestic production capacity was addressed in section 3.6.4 and is explored later in the simulations).

Then, we can calculate the overall carbon intensity of the fuel consumed by conventional vehicles by the share of gasoline and ethanol in the liquid fuel-mix using the following equation:

$$I_{CV} = F_{eth} * I_{eth} + (1 - F_{eth}) * I_{gas} \tag{16}$$

where I_{CV} is the average carbon intensity per unit energy of the gasoline-class fuel used by conventional vehicles, F_{eth} is ethanol's share of the fuel mix from equation (10), I_{eth} is the average carbon intensity of the ethanol content from equation (15), $(1 - F_{eth})$ is the share of gasoline the fuel mix, and I_{gas} is the carbon intensity of gasoline.

3.7.2 Calculating GHG emissions

The greenhouse gas emissions were divided into two main categories: those from the gasoline-class fuel mix for conventional vehicles, and those from electricity generation for electric vehicles. For a well-to-wheels analysis of emissions from fuel use for each vehicle type—electric vehicle or conventional vehicle—we use the following formula:

$$G_{k,t} = D_{k,t} * E_{k,t} * I_{k,t} \tag{17}$$

where $G_{k,t}$ is the greenhouse gas emissions from vehicle type *k* in year *t*, $D_{k,t}$ is the total distance travelled by all vehicles of type *k* in year *t*, $E_{k,t}$ is the amount of energy required per km of travel for vehicle type *k* in year *t* (based on fuel/energy efficiency of the vehicles), and $I_{k,t}$ is the carbon intensity per unit of energy used to power vehicle type *k* in year *t*.

The total GHG emissions from light duty vehicle travel in a given year are then calculated as follows:

$$Total\ GHG\ emissions\ in\ year\ t = G_{EV,t} + G_{CV,t} \tag{18}$$

taking the sum of the greenhouse gas emissions, *G,* from EVs and CVs in year *t,* gives the total GHG emissions from light duty vehicles in a given year.

3.8 Model verification

In order to verify the computer model against historic data, the model was run using values for tank-to-wheel GHG emissions from transportation fuels, as those are the only figures available from the British Columbia GHG Inventory Report (BC Provincial Government, 2014). We did not change any of the previously discussed parameters for the model, except for the carbon intensities of gasoline and ethanol, which were represented by the amount of CO_2e released when each fuel is burned—2.299kg/L for gasoline, and 1.504 kg/L for ethanol (BC Ministry of Environment, 2014b). The simulated tank-to-wheel emissions from 2000 to 2013 are shown alongside the historic values from the BC GHG Emissions Inventory Report in figure 3.5. Results from the verification show a mean absolute error of 2.36% from the historic values.

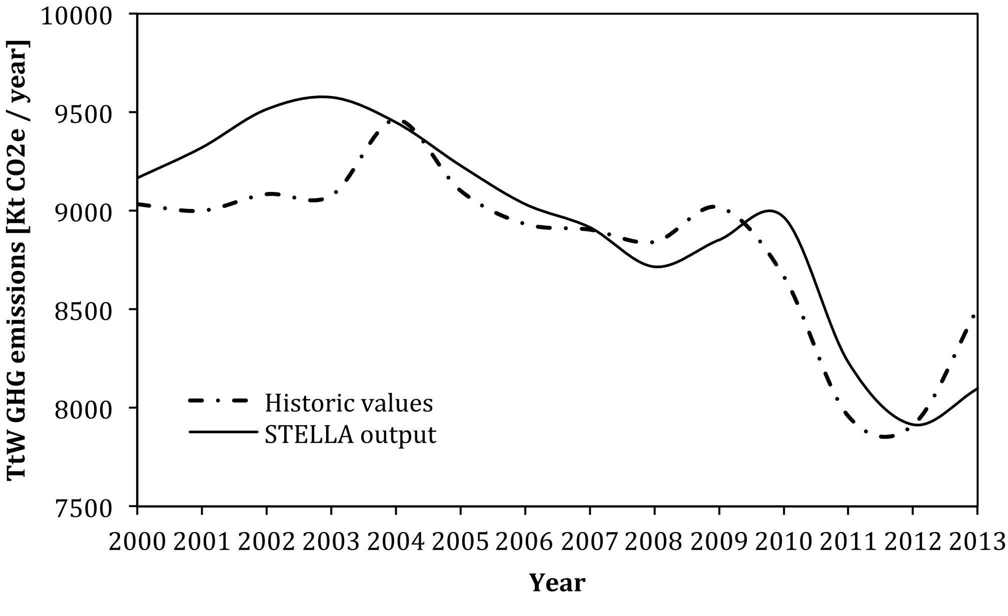


Figure 3.5 Simulated GHG emissions from light duty vehicles alongside historic values (BC Provincial Government, 2014) for comparison.

The peaks and valleys in the simulated output can be attributed to fluctuations in gasoline prices and personal income, which caused changes in annual travel demand relative to the assumed elasticities discussed previously. Furthermore the downward trend is accentuated in the model by increased fuel efficiency in the conventional vehicle stock, which improved from 12 Lge/100km in 2000, to 10.8 Lge/100km in 2013. Observing the historic and simulated curves, they appear to exhibit similar behaviour, showing similar peaks, valleys, and downward trend over the time period.

Over the verification time-period, emissions were determined mainly by annual gasoline consumption. The impacts of electric vehicles and bioethanol over this time period were so small as to be relatively inconsequential. Therefore the verification performed here essentially serves to test the model's ability to simulate GHG emissions from conventional vehicles based on fluctuations in travel demand and fuel efficiency, which are in turn based on changes in gasoline price and personal income. The verification does not test the model's ability to simulate competition between electric vehicles and conventional vehicles (as there is not yet robust data to compare against), nor the integration of higher concentrations of bioethanol into the fuel mix.

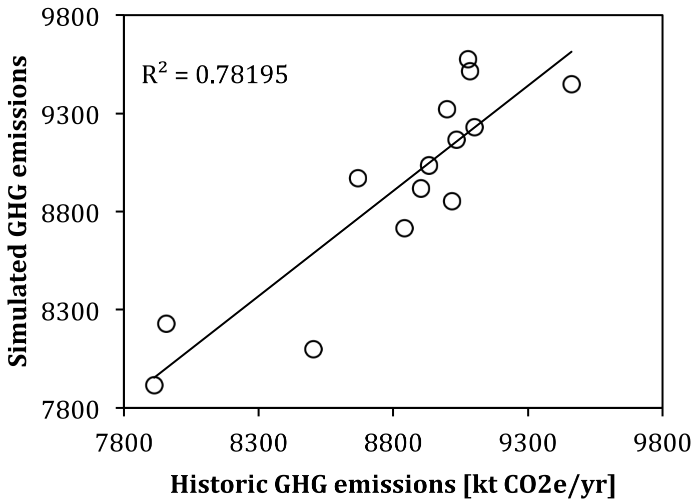


Figure 3.6 Results from regression analysis on simulated output versus historic data.

To further compare the simulated and historic GHG emissions from light duty vehicle travel, a simple linear regression analysis was performed to test the similarity of the curves to one another (figure 3.6). The r-squared coefficient was found to be 0.78, implying that 78% of the variation in annual GHG emissions can be explained by the model. Thus we conclude that over the verification period, the modelled output is a satisfactory fit to the historic data.

Disagreement between the modelled output and the historical data could have resulted from a number of reasons. The model uses changes in average annual fuel price and personal income to predict travel demand, and changes in fuel costs per km of driving to predict the trend in fuel efficiency of the vehicle stock. The retail gasoline prices used in the simulation could be a cause of some of the disagreement, as they are a yearly average, which do not reflect major fluctuations that may have occurred within the year and affected vehicle travel in the short term. Also, using GDP per capita as a proxy for personal income in the model may misrepresent some changes to actual personal incomes in the province. Furthermore, there could be many behavioural factors outside of our predictors that have influence on vehicle travel and fuel consumption in the province, but identifying these is beyond the scope of this study.

The most notable discrepancy in the verification occurs in the latter part of figure 3.5, where the simulated output appears to lag behind the historic data by one year (for example, the peak in 2009 in the historic data appears in 2010 in the simulated data). However, as the observed phase-shift appears to be one year, and the simulation time is 50 years, we believe that by the year 2050 in the simulation, a time lag of one year will be negligible to the overall outcome of the simulation.

It is important to note that over the verification period, historic exogenous inputs (e.g. gasoline price and personal income) were used in the simulation. The simulation from 2014 to 2050, which we use to project annual GHG emissions from light duty vehicles under various assumptions, uses projections for gasoline price and personal income that are produced from other modelling studies and exogenously applied to our model. To that effect, we essentially import errors from these projected values that are not accounted for in the verification shown here. Therefore based on the observed curves, the mean absolute error, and the r-squared value, we are satisfactorily confident in the model's ability to simulate realistic GHG emissions from light duty vehicle travel that result from our assumptions, but uncertainties associated with those assumptions make it difficult to assess confidence in the predicting power of the model to the year 2050. Thus outcomes from the simulations conducted here are not claimed to accurately represent the future of light duty vehicle travel in British Columbia, but instead explore potential scenarios based on our assumptions and the errors inherent in them.

When run in in well-to-wheel mode, the simulated GHG emissions from 2000 to 2013 are 32% higher than the historic emissions, due to the added carbon intensity from measuring their lifetime impact. This corresponds to a review of lifecycle assessments of Canadian oil sands crudes, which finds that upstream emissions from production and transportation of the fuel account for 27% to 39% of the well-to-wheel emissions (Lattanzio, 2014). The simulated curve of well-to-wheel emissions from 2000 to 2013, while higher than tank-to-wheel emissions follows exactly the same shape during the verification time period. Thus the well-to-wheel emissions are not depicted in the above graphic as it was purely for verification purposes but will be used in all of the following simulations.

4 Results: Modelled projections to 2050

The following projections are outputs from the STELLA® model, under the assumptions discussed in section 3. Any changes to assumptions for scenario analyses are mentioned where necessary, but otherwise they are according to section 3. All scenarios are run over the time period from 2000 to 2050 with a timestep of 0.1 years. To begin with, a baseline scenario was determined that projects the vehicle and fuel markets, and travel characteristics under business-as-usual assumptions. Next, scenarios were explored that increased the level of EV adoption in the province; following that, increased incorporation of bioethanol into the fuel mix was modelled; and finally model sensitivity to various policy intervention measures was explored.

4.1 Determining a baseline scenario

To determine a baseline scenario for the following simulations to be compared against, we ran the model according to the assumptions described in section 3, and with only the EV and biofuel policies currently in place in British Columbia. Those policies, and key assumptions from the previous *Methods* chapter affecting travel demand, EV adoption, and GHG emissions are listed in table 4.1. Table 4.1 is not comprehensive, but highlights important areas for the upcoming scenario analyses and discussions.

Table 4.1 Key assumptions for baseline case scenario.

Parameter	**Assumption**
EV purchase price relative to conventional vehicle	2.25 in 2000, linearly decreasing to 1.25 in 2050
EV purchase incentive	\$5000 from 2011-2017; \$0 after 2017
Available variety of EV models	Constant at 8 models after 2016
Consumer familiarity with EV	Initial value of 14%; progresses endogenously
Ethanol content in fuel mix	Constant at 5% by volume
Carbon intensity of gasoline-class fuel (including ethanol)	Constant at 87.29 g CO_2e/MJ
Carbon intensity of electricity	2.78 g CO_2e/MJ (10.0 g CO_2e/kWh)
Fuel efficiency of conventional vehicles	Endogenous, constrained by U.S. CAFE standards
Energy efficiency of EV	20.0 kWh/100km to 2016, linearly decreasing to 14.8 kWh/100km in 2050
Retail gasoline price	NEB (2016): *Canada's energy future* projections to 2040: reference scenario (see Appendix B for curves)
Residential energy price rate	
Personal income	

4.1.1 Baseline characteristics that persist across all scenarios

The following results describe the baseline figures for travel demand, vehicle market composition, and annual GHG emissions from light duty vehicles in British Columbia. The main factors that persist across all simulations are the growth of the vehicle stock, the annual travel demand per vehicle, and the average fuel efficiency of conventional vehicles. Based on our assumptions, we project the total light duty vehicle stock to grow 25% from 2015 to 2050, from 2.8 million to 3.5 million vehicles (figure 4.1). The average annual travel demand per conventional vehicle fluctuates mainly between the years 2000 and 2015, when large fluctuations are observed in historic gas price and personal income data. After 2015, the per car travel demand gradually increases as personal incomes are projected to rise at a faster rate than the gasoline price. Thus the average km travelled per vehicle per year begins at 14,975 km in 2000, falling to under 12,000 in 2012 and climbs again to 14,800 km in 2050 (figure 4.1).

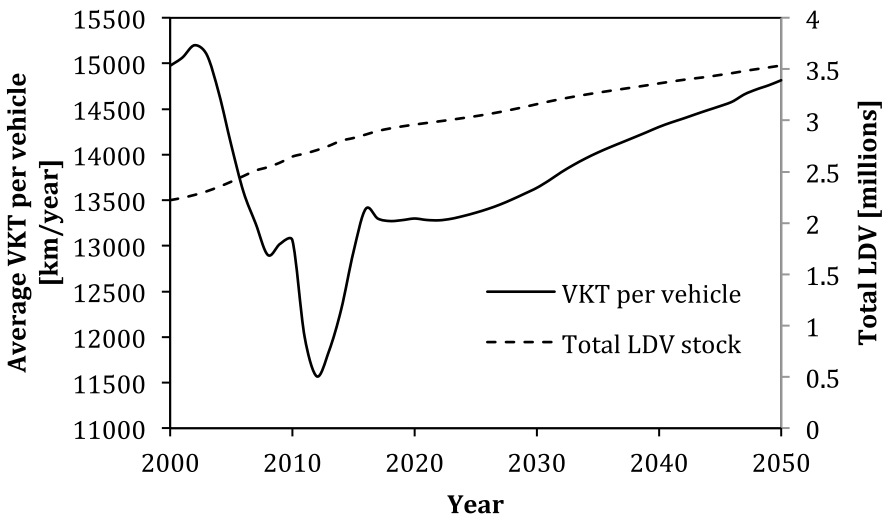


Figure 4.1 Total light duty vehicle (LDV) stock and average distance travelled per vehicle (VKT) in years 2000 to 2050.

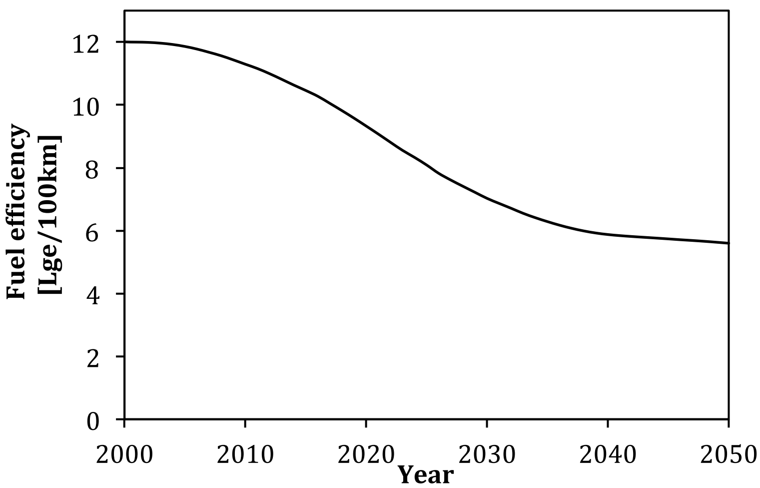


Figure 4.2 Average fuel efficiency of light duty conventional vehicles from 2000 to 2050.

Figure 4.2 shows the progression of the average fuel efficiency of the conventional vehicle stock to 2050. As the cost of driving was assumed to influence the demand for fuel-efficient conventional vehicles, we found that over the course of the simulation, constantly increasing gasoline prices (after 2015) caused a shift in demand towards high-efficiency vehicles within the conventional vehicle stock. As a result, the average fuel efficiency of conventional vehicles improved from 12.0 Lge/100km in 2000 to 5.6 Lge/100km in 2050, following a decreasing sigmoidal curve. This projection is comparable to the U.S. Energy Information Administration's Annual Energy Outlook, which projects average fuel efficiency of 6.4 L/100km for the U.S. light duty vehicle stock in 2040 (EIA, 2015).

4.1.2 Baseline for EV adoption

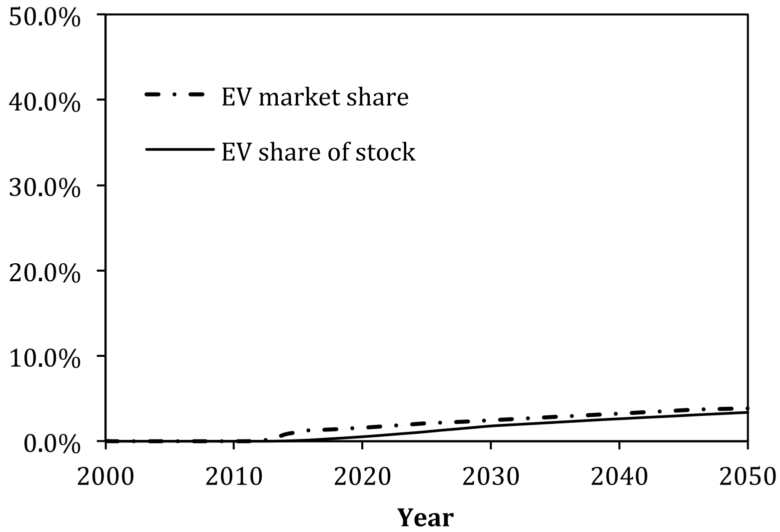


Figure 4.3 Market share and share of total light-duty vehicle stock for EVs under baseline scenario assumptions.

Table 4.2 Baseline figures for EV market penetration in target years and latest historic value for context.

Year	Market share (% sales)	Share of on-road stock (%)	Total EV on-road stock
2014[a]	0.5%	<0.1%	1700
2015[b]	1.1%	<0.1%	2497
2020	1.6%	0.5%	15617
2050	3.9%	3.4%	119493

a. Latest historic values from (ICBC, 2016). Market share is author's calculation based on difference in EV population between 2013 and 2014, and total vehicle sales.
b. Values from 2015 onward are simulated outputs.

Electric vehicle demand and their share of the on-road light duty vehicle stock are demonstrated in figure 4.3. Electric vehicle sales are shown to remain very low over the course of the simulation, and therefore so too does electric vehicles' share of the light duty vehicle stock. In table 4.2, the latest available data, as well target years (in terms of emissions reductions) are highlighted. Based on our assumptions of the vehicle market, the number of EVs on the road grew from 1700 vehicles in 2014 (ICBC, 2016) to 2497 vehicles in 2015. Actual 2015 numbers are not available yet, but one source reported an estimate of 2419 (Stevens, 2016), which is slightly less than our simulated value. By 2050, the model projects that EVs will comprise 3.4% of the on-road stock, placing 119 thousand EVs on the road. The main constraints to EV adoption were lack of familiarity with the product and lack of variety to choose from (as defined in section 3.3.7). We assumed that no measures were taken to boost familiarity with EVs, and as a result, consumer familiarity increased only moderately from 14% of consumers in 2015 to 25% in 2050 due to the minimal projected increase in EVs' share of the vehicle stock. Also, no new EV models entered the market after 2016, and as a result, from 2016 onward, 60% of consumers who would have purchased an EV (the latent demand) were not able to find a model suitable for their preferences. Due to these constraints on EV market penetration, the realized demand only reached 1.6% and 3.9% of all light duty vehicle sales in 2020 and 2050 respectively.

4.1.3 Baseline GHG emissions

Annual GHG emissions from light duty vehicle travel in the business-as-usual baseline scenario can be seen in figure 4.4. The scenario illustrated here will be used as the base case against which all other scenarios are compared. In measuring change to annual GHG emissions, we use 2007 as the reference value, as that is the reference year for British Columbia's GHG emission reduction targets for 2020 and 2050. As is illustrated in figure 4.4 and summarized in table 4.3, the well-to-wheel GHG emissions show a reduction of 6% in 2020 and 27% in 2050 from the 2007 reference year.

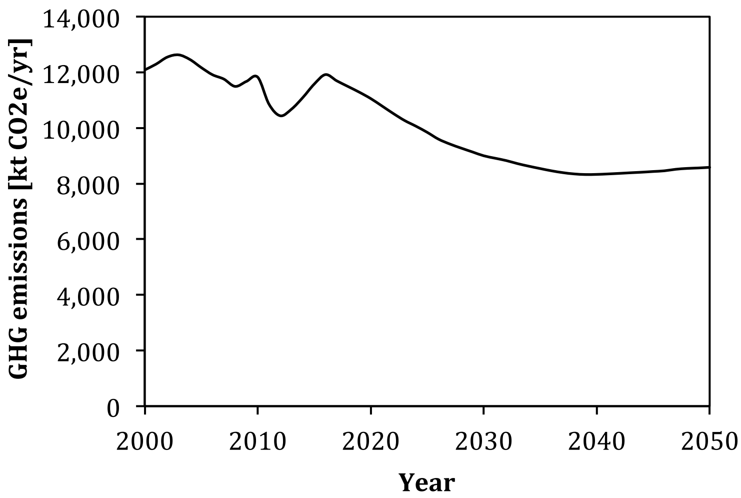


Figure 4.4 Annual well-to-wheel GHG emissions from light duty vehicles under baseline assumptions.

Table 4.3 GHG emissions from light duty vehicles [kt CO_2e/year] in target years under baseline assumptions, and the percent reduction from 2007 levels.

Year	**2007**	**2015**	**2020**	**2050**
Emissions	11759	11577	11059	8585
% below 2007		2%	6%	27%

The reduction in emissions shown in the baseline scenario can mainly be attributed to the CAFE standards for fuel efficiency assumed to be followed by automobile manufacturers. Based on our assumptions in the new conventional vehicle market, the average fuel efficiency of all conventional vehicles on the road improved from 11.7 Lge/100km in 2007 to 5.6 Lge/100km in 2050 during the simulation. In our model, the increase in efficiency came about due to increasing fuel prices, which made high efficiency vehicles more attractive than low-efficiency vehicles, and thus the market followed more closely the progress of smaller, higher-efficient compact cars whose efficiency ratings continued to improve following the CAFE standard.

4.2 Electric vehicle adoption scenarios

Now we explore three cases for market penetration of electric vehicles wherein availability and familiarity constraints are removed. For the following three cases, all initial baseline assumptions remain the same (recall table 4.1) except those directly related to EV availability and EV familiarity. Table 4.4 highlights the differences between assumptions for the three EV adoption scenarios, alongside the baseline scenario.

Table 4.4 Key differences in assumptions between electric vehicle adoption scenarios.

	Assumption			
Parameter	**Baseline**	**Case 1**	**Case 2**	**Case 3**
Available variety of EV models	Constant at 8 models on market after 2016	As in baseline	Gradual increase to 20 models on market by 2030	As in Case 2
Consumer familiarity with EV	Initial value of 14%; progresses endogenously	Jump to 100% of consumers in 2016	As in baseline	As in Case 1

In **Case 1 (constrained by availability)**, we assume that the number of available EV models on the market stays constant at 8 between 2016 and 2050, but we also assume 100% of consumers are familiar with EVs. **Case 2 (constrained by familiarity)** assumes that between 2016 and 2030 the number of EV models widely available for the consumer to choose from will increase gradually from 8 to 20, but familiarity remains the same as in the baseline assumption (i.e. initially 14% of consumers are familiar with EVs and progresses endogenously over the course of the simulation). In **Case 3 ('unconstrained')**, we assume that 20 EV models gradually become available by 2030, and 100% of consumers are familiar with EV technology by 2016. The following are the results from the three constraint case scenarios alongside the baseline (full constraint) scenario.

4.2.1 Market penetration

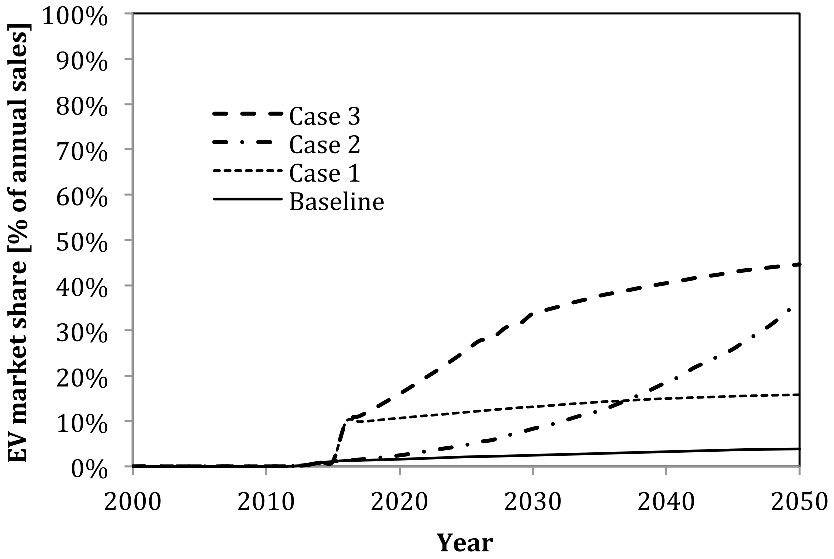


Figure 4.5 EV market share as a percentage of annual light duty vehicle sales under 3 constraint scenarios with baseline scenario for reference.

Table 4.5 Market share of EVs (% of annual sales) in target years under four constraint scenarios.

Year	Baseline	Case 1	Case 2	Case 3
2015	1.1%	1.1%	1.1%	1.1%
2020	1.6%	10.6%	2.4%	16.0%
2050	3.9%	15.8%	36.7%	44.6%

Figure 4.5 shows the market share of electric vehicles as a percentage of the total light duty vehicle sales in each year; and target years are highlighted in table 4.5. In **Case 1**, there is a large spike in the EV market share between 2015 and 2016. This is because we assume that consumer familiarity increases suddenly from 14% to 100% in 2016. However, after 2016, the market share of EVs settles into very slow growth, as demand is still constrained by lack of variety in the market place. In 2020 the market share is 11% and by 2050, it reaches 16%.

In **Case 2**, the market share of EVs appears to increase exponentially, although shortly after 2050, it is expected to level off once EV market share reaches saturation. The slow initial growth of EV sales in this case is due to consumers' lack of familiarity with the technology. Although the variety of EVs is stepwise increasing until there are 20 models to choose from in 2030, actual sales lag behind while familiarity among consumers grows. Between 2020 and 2050, significant growth in EV sales are exhibited, as the market share climbs rapidly from 2% to 37% on account of positive feedback in the consumer familiarity causal loop.

The curve exhibited in **Case 3** we consider as the maximum for market share of EV over the time frame of the simulation. As in case 1, the large spike in sales in 2016 is from the assumed increase in familiarity from 14% to 100% of consumers. However, unlike case 1, the market share of EVs in case 3 continues to grow rapidly until all 20 EV model varieties are available to the public in 2030. At this point, growth begins to slow down as all availability and familiarity constraints have been removed. However, positive feedback loops within the model cause the EV market share to continue to grow, as the increased presence of EVs in the light duty vehicle stock not only leads to more sales but also to a higher potential for sales—due to higher visibility, social demand, and investments in infrastructure. This growth allows EVs to capture 45% of the market share in 2050.

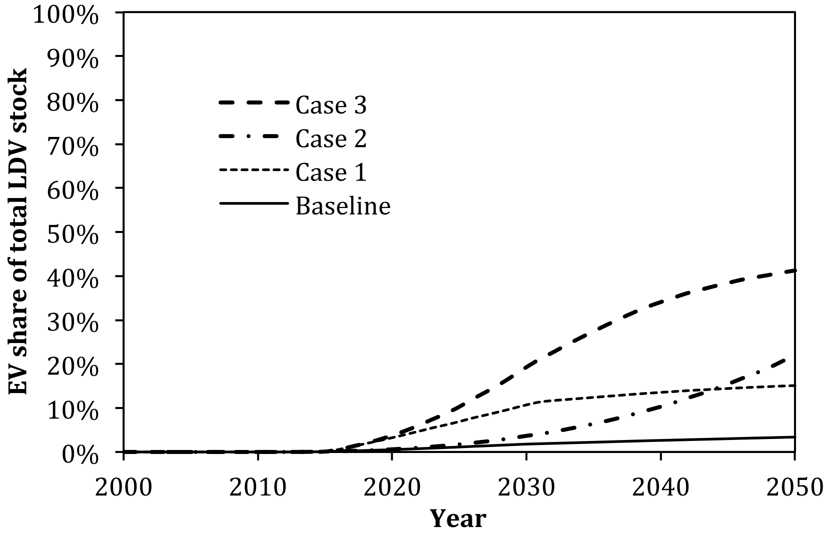


Figure 4.6 EV share of the light duty vehicle stock under the four constraint scenarios.

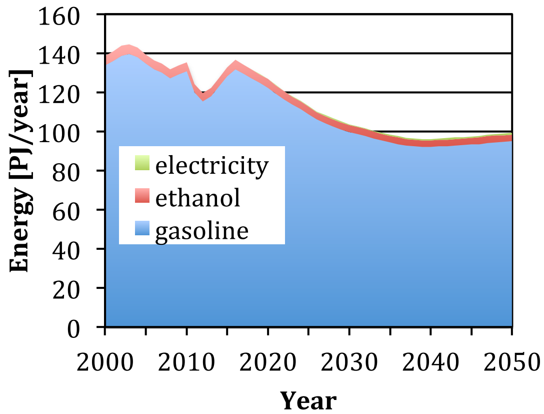
Table 4.6 EV on-road stock and corresponding shares of the total light duty vehicle stock in target years.

	Year	Baseline	Case 1	Case 2	Case 3
EV stock (units)	2020	15617	95848	17910	111125
	2050	119493	534027	780655	1458934
Share of stock	2020	0.5%	3.2%	0.6%	3.8%
	2050	3.4%	15.1%	22.1%	41.3%

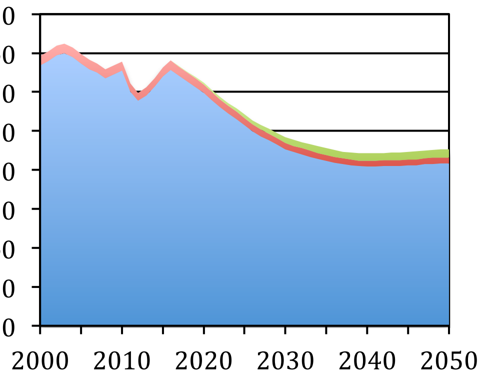
The percentages of EVs in the provincial light duty vehicle stock under the various constraint scenarios are illustrated in figure 4.6 with target years summarized in table 4.6. The curves all follow a similar shape to their respective market share curves from figure 4.5, yet exhibit a delay due to the lifetime of vehicles on the road (i.e. the turnover of the vehicle stock is 16 years). In all cases, based on our assumptions, electric vehicles' share of the light duty vehicle stock remains relatively low in 2020—the largest share is exhibited in case 3 where EVs make up 4% of the light duty vehicle stock. After 2020, the modelled scenarios deviate more significantly from one another, and as a result we see EVs potentially making up between 3% and 41% of the on-road stock by 2050 depending on various constraints to their adoption. This translates to between 119 thousand and 1.46 million EVs on the road in 2050—a very wide range of possibilities, the implications of which will be discussed later.

4.2.2 Annual energy demand

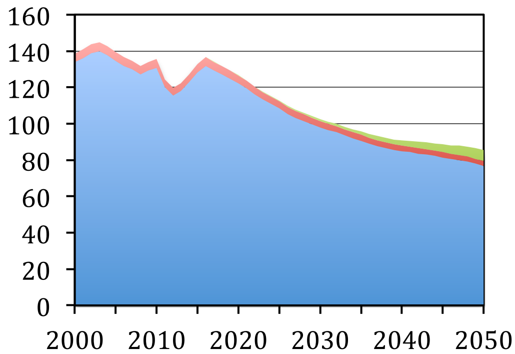
A very visible upshot of increased electric vehicle adoption is the impact on the annual energy demand from light duty vehicle travel. Figure 4.7 shows the annual energy required to power the vehicle stock under the four EV adoption scenarios. In all four scenarios there are the same total number of vehicles on the road with the same annual travel demand. However, as the EV share of the total vehicle stock increases, the total energy demand decreases since electric vehicles exhibit significantly higher energy efficiency than conventional vehicles. So, not only are electric vehicles powered by a low-carbon energy source (in the context of this study), but they also use the energy more efficiently and thus require less of it than their conventional counterparts.



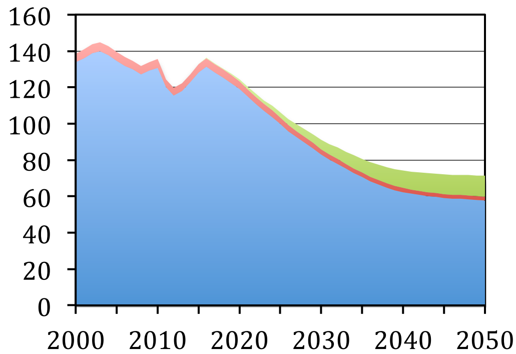
Baseline: EV growth constrained by availability and familiarity



Case 1: EV growth constrained by availability



Case 2: EV growth constrained by familiarity



Case 3: No availability or familiarity constraints

Figure 4.7 Annual energy demand from the light duty vehicle stock decomposed into fuel type (gasoline, ethanol, and electricity). Results from the four constraint scenarios.

Table 4.7 Total energy consumption in target years [PJ] displayed along with the per cent reduction in emissions in 2050 from 2007 levels.

Year	Baseline	Case 1	Case 2	Case 3
2007	135	135	135	135
2020	127	125	127	124
2050	99	91	86	71
% reduction	25%	33%	36%	47%

Table 4.7 summarizes the decreases in annual energy demand on account of varying degrees of EV adoption. In the baseline scenario annual energy use is reduced to 25% below 2007 levels in 2050 mainly due to efficiency improvements in the conventional vehicle stock. In case 3, due to high market penetration of EVs on top of improvements to conventional vehicles, the annual energy consumption in 2050 is 47% below 2007. Comparing the baseline scenario with case 3, the total energy demand in 2050 drops from 99 PJ (MJ x 10^9) to 71 PJ—a 28% difference in the overall energy efficiency of the total vehicle stock.

Table 4.8 EV share of the light duty vehicle stock and share of annual energy consumption in target years in four modelled scenarios.

Year	Baseline		Case 1		Case 2		Case 3	
	stock	energy	stock	energy	stock	energy	stock	energy
2020	0.5%	0.1%	3.2%	0.7%	0.6%	0.1%	3.8%	0.8%
2050	3.4%	1.0%	15.1%	4.7%	22.1%	7.2%	41.3%	16.1%

Table 4.8 displays the EV share of the total light duty vehicle stock alongside EV share of the annual energy consumption for our 4 case scenarios. The improved energy efficiency of EV over conventional vehicles becomes even more apparent when considering that in case 3, only 16% of the annual energy demand is required to power an EV population that makes up over 41% of the total vehicle stock. In other words, conventional vehicles, although reduced to 59% of the total light vehicle stock in 2050 in case 3, still make up 84% of the total energy demand, and therein illustrates the great potential for reducing energy demand by offsetting gasoline vehicles with electric vehicles.

4.2.3 GHG emissions

The resulting GHG emissions from the three constraint cases alongside the baseline scenario are illustrated in figure 4.8, with reductions in target years summarized in table 4.9. The results show that by 2050, cases 1, 2, and 3 lead to additional GHG emission reductions of 9%, 14%, and 28% respectively when compared to the baseline. The additional reductions in emissions can be attributed to the offsetting of gasoline power with electricity. The greatest GHG reduction comes in case 3, wherein the adoption of 1.46 million EVs in the vehicle stock leads to an offset of over 1 billion litres of gasoline in the year 2050. So, with varying levels of EV adoption between now and 2050, the total GHG emissions from the light duty vehicle stock could see a reduction of between 27% and 55% compared to 2007 levels.

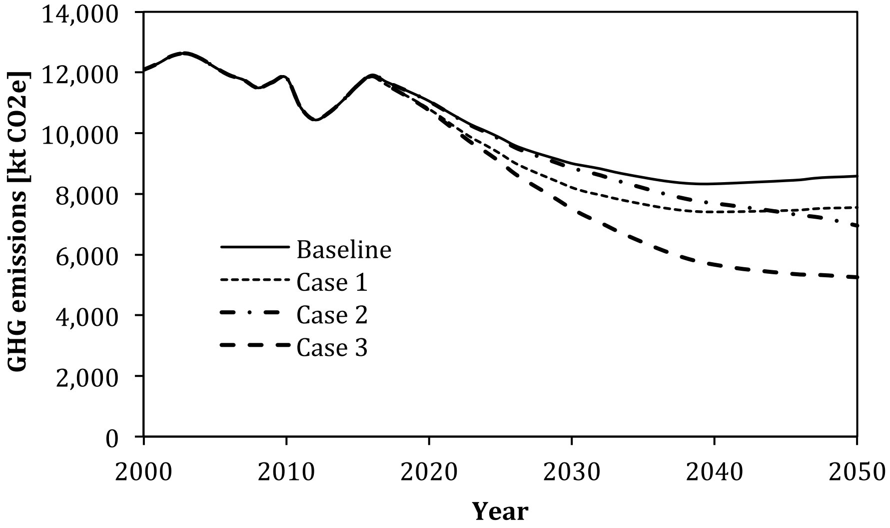


Figure 4.8 Annual well-to-wheel GHG emissions from light duty vehicles under the four modelled constraint scenarios.

Table 4.9 GHG emissions reductions from 2007 level for the four modelled constraint cases.

	Year	Baseline	Case 1	Case 2	Case 3
Reduction from 2007	2020	6%	8%	6%	9%
	2050	27%	36%	41%	55%

4.3 Combining a bioethanol strategy with electric vehicle adoption scenarios

Here, we look into how British Columbia might reduce the carbon intensity of the gasoline class fuel-mix, and how this could affect GHG emissions from light duty vehicles through to 2050 relative to the baseline scenario. According to BC's Renewable and Low Carbon Fuel Requirements Regulation, the gasoline fuel mix must maintain a minimum of 5% renewable content, and achieve a 10% decrease in carbon intensity between 2012 and 2020. However, to achieve such a reduction in carbon intensity would likely require a combination of significantly higher renewable content and lower lifetime-carbon gasoline. In the baseline scenario (outlined in section 4.1) we assumed that the carbon intensity of the gasoline-mix including ethanol content remained constant at the default value set by the provincial government. The following considers using bioethanol as a means to reduce the carbon intensity of the fuel mix.

Given the low amount of renewable content in the gasoline blend, we concede that meeting a 10% reduction in carbon intensity by 2020 would require lower-carbon gasoline sources as well as the purchase of carbon offsets or paying penalties that are outside the scope of this study. Thus we do away with the 2020 deadline for a 10% carbon intensity reduction, and instead look into a long-term strategy to incorporate BC forest derived cellulosic ethanol into the fuel mix and examine the potential for reducing the carbon intensity of the fuel-mix by 2050.

Significantly reducing the carbon intensity of the fuel mix by ethanol integration relies not only on adding a greater concentration of lower-carbon ethanol to the gasoline pool, but also on ensuring the consumer has access to higher ethanol blends and a vehicle compatible with high ethanol fuel. With that consideration, an '**ethanol push**' strategy was developed here that aims to incorporate a high share of low-carbon ethanol into the annual fuel sales to conventional vehicle drivers. The key assumptions for ethanol push strategy alongside the baseline scenario for comparison are listed in the top section of table 4.10.

Table 4.10 Key assumptions for the ethanol push strategy and modelled ethanol push scenarios alongside baseline assumptions.

Parameter	**Baseline**	**Ethanol push strategy**	
Minimum ethanol concentration in fuel	5% by volume	Increase linearly from 5% to 10% by volume between 2015 and 2020	
Carbon intensity of fuel mix	Constant at 87.29 g CO_2e/MJ	Progresses based on composition of the fuel mix[a]	
Flex fuel vehicle market share	N/A	Grows linearly to 96% of annual CV sales in 2020 and thereafter	
E85 pump installation rate	0	10 stations per year starting in 2017	
Cellulosic bioethanol plants constructed	0	3; completed in 2021, 2028, and 2037 respectively	
Ethanol production capacity (per plant)	N/A	200 million L/year	
	Baseline	**Low EV + ethanol push[b]**	**High EV + ethanol push[b]**
Available variety of EV models on market	Constant at 8 models after 2016	As in baseline	Increase gradually to 20 models by 2030
Consumer familiarity with EV	Initial value of 14%. Progresses endogenously	As in baseline	Jump to 100% of consumers in 2016

a. Determined by share of fuels in the fuel mix with the following carbon intensities:
- Gasoline: 90.21 g CO_2e/MJ
- Imported ethanol: 53.11 g CO_2e/MJ
- Forest-derived ethanol: 14.05 g CO_2e/MJ

b. Includes all the above 'ethanol push' assumptions, plus the EV adoption assumptions beneath.

We focus on boosting the share of ethanol in the fuel mix by increasing the minimum ethanol concentration from 5% to 10% by volume, and by promoting the uptake of E85 through increased vehicle compatibility and access to the fuel. As mentioned earlier, we assume that a consumer will choose E85 over the regular gasoline-class fuel when presented with the option. So in this simulation, E85 compatibility and accessibility translates directly into E85 sales regardless of economic or behavioural factors. Furthermore, we aim to lower the carbon intensity of the ethanol consumed, by incorporating second-generation cellulosic ethanol from forestry residues in British Columbia. The ethanol push involves the construction of three cellulosic bioethanol plants in BC, each with a production capacity of 200 million L/year, in order to offset imported first-generation ethanol.

We ran the ethanol push simulation over two EV adoptions scenarios, in order to gauge the ethanol push with varying composition of the light duty vehicle stock. The latter part of table 4.10 highlights the differences between the two scenarios and the baseline scenario in terms of assumptions impacting EV adoption. The '**Low EV + ethanol push**' scenario combines low EV growth, as in the baseline scenario, with the ethanol push strategy, while the '**High EV + ethanol push**' scenario combines the highest level of EV adoption, as in case 3 previously, with the ethanol push strategy. Baseline EV adoption and Case 3 EV adoption were chosen in order to compare the effects of an ethanol push with what we consider to be the maximum and minimum number of conventional vehicles on the road over the course of the simulation. The following sections describe the results from the two modelled ethanol push scenarios.

4.3.1 Annual energy demand

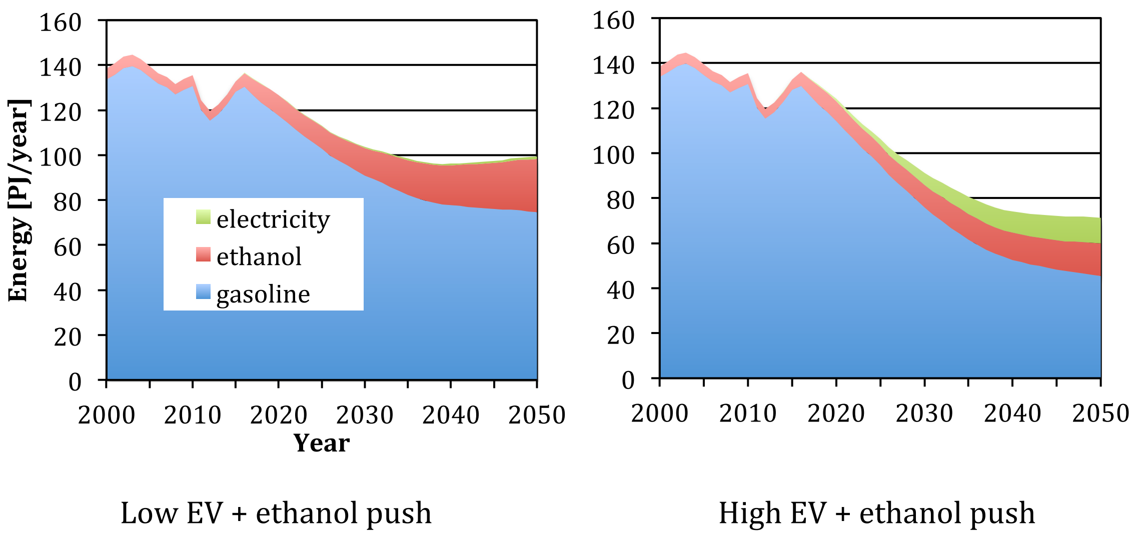


Figure 4.9 Annual energy demand from the light duty vehicle stock decomposed into fuel type. Results from the 'ethanol push' scenario with low and high EV adoption.

The decomposition of the energy demand by fuel type under the two ethanol push scenarios is illustrated in figure 4.9. The annual energy consumed by the entire vehicle stock is the same as in the baseline and Case 3 scenarios outlined in the previous section. I.e. the energy demand in 2050 is 99 PJ in the 'Low EV + ethanol push' scenario, and 71 PJ in the 'High EV + ethanol push' scenario. However, ethanol now contributes 24% of the overall energy supply in the low EV scenario, and 20% of the energy supply in the high EV scenario. Higher concentrations of ethanol do not decrease the amount of energy required to power the conventional vehicle stock since engines operating on higher ethanol blends do so with the same *energy efficiency* as if operating on gasoline only. Thus the offset of gasoline consumption with ethanol works purely to reduce the reliance on fossil fuels and their impacts and *not* to reduce energy demand.

4.3.2 Ethanol supply

In both of the scenarios presented here, by 2050 ethanol makes up 32% of the liquid fuel mix by volume, instead of 5% as in the baseline scenario. The higher concentration of ethanol in the liquid fuel mix resulted from a combination of increasing the minimum ethanol concentration in the regular gasoline blend from 5% to 10%, and from increasing the availability of, and compatibility of conventional vehicles with, E85 fuel. By 2050, flex-fuel vehicles comprise 96% of the conventional vehicle stock. Furthermore, by installing E85 pumps in gasoline stations at a rate of 10 stations per year, 15% of the over 2000 gas stations in BC will be able to supply E85 to the consumer by 2050. Based on our assumptions, this translates into 29% of the conventional vehicle stock operating on E85 fuel and the remaining conventional vehicles using E10. However, although ethanol makes up 32% of the liquid fuel-mix by volume in 2050, due to its lower energy density it only offsets 24% of the gasoline sales.

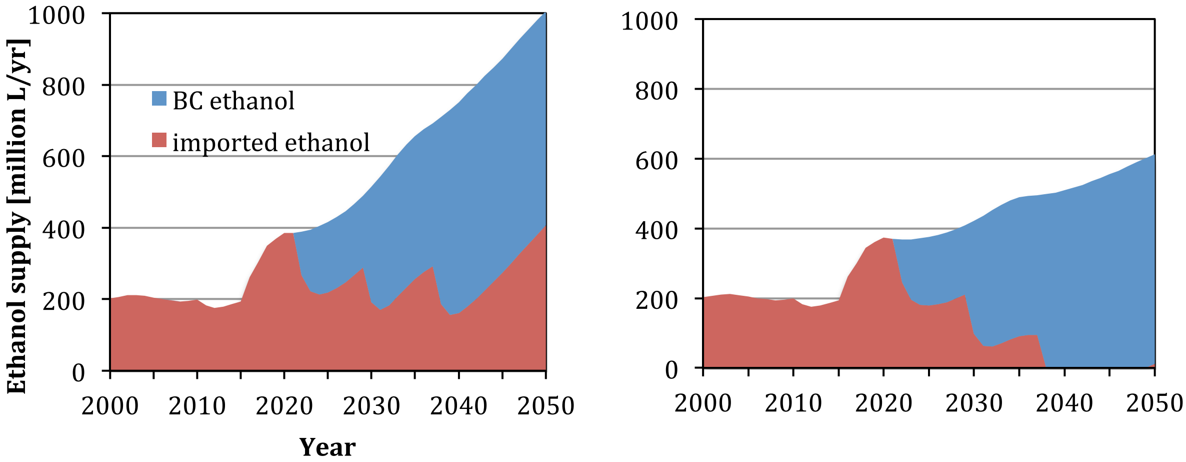


Figure 4.10 Ethanol supplied to the light duty vehicle stock decomposed into imported and domestic supply under the 'ethanol push' scenario with low and high EV adoption.

Because the number of conventional vehicles on the road greatly differs between low EV and high EV scenarios, so too does the demand for ethanol. In the 'Low EV + ethanol push' scenario, over 1 billion litres of ethanol are consumed in the year 2050, while in the 'High EV + ethanol push' scenario, the demand just barely exceeds 600 million litres (figure 4.10). As we assumed the construction of 3 bioethanol plants in British Columbia to be completed between 2021 and 2037, the total production capacity for ethanol after 2037 is 600 million litres per year. In the Low EV scenario, these 600 million litres meet 60% of the annual ethanol demand in 2050, while in the High EV scenario they meet 100% of the ethanol demand from 2038 to 2049, before increased demand requires an additional 2% from imports in 2050.

4.3.3 Carbon intensity of gasoline-class fuel

In each case modelled here, the remainder of the ethanol demand would need to be met with imported product, from out of province or out of country, which we assume has the average carbon intensity of first-generation ethanol. Furthermore, since we assumed that a forest-derived cellulosic ethanol from British Columbia's forestry residues offers a 74% reduction in lifetime carbon intensity compared to imported first-generation ethanol (14.05 g CO_2e/MJ versus 53.11 g CO_2e/MJ), then the carbon intensity of the fuel mix varies depending on the composition of the renewable content.

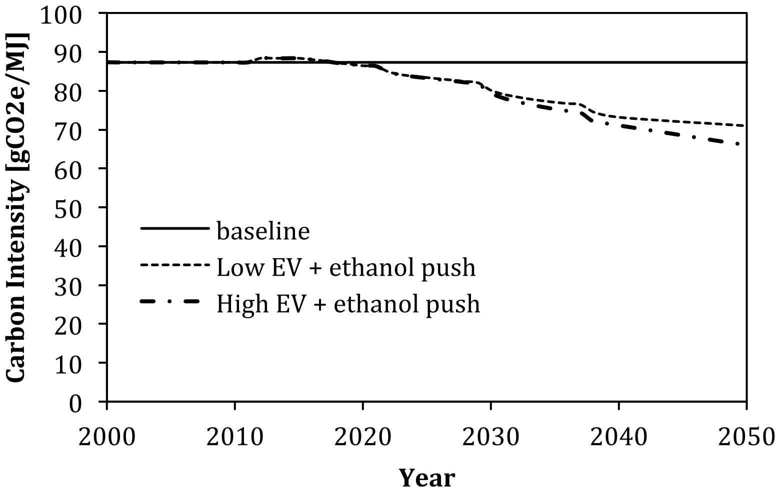


Figure 4.11 Average carbon intensity of the liquid fuel mix under the two 'ethanol push' scenarios and the baseline scenario.

Table 4.11 Carbon intensities [g CO_2e/MJ] of the ethanol supply, and of the overall fuel mix in target years. Ethanol concentration in the fuel mix reaches 32% in both scenarios.

	Low EV + ethanol push		**High EV + ethanol push**	
Year	**Ethanol CI**	**Overall CI**	**Ethanol CI**	**Overall CI**
2012	53.11	88.35	53.11	88.35
2020	53.11	86.42	53.11	86.42
2050	29.82	70.96	14.83	66.18
% reduction from 2012	44%	20%	72%	25%

In figure 4.11, the carbon intensity of the fuel mix under 'Low EV + ethanol push', and 'High EV + ethanol push' scenarios are illustrated along with the baseline scenario. In 2012, the carbon intensity of the fuel mix in both ethanol push scenarios rises above the baseline. This occurs because in 2012, historical data for the carbon intensity of gasoline class fuel became available, whereas before 2012 the carbon intensity of the fuel mix including ethanol was assumed to be a flat value. In the baseline, we assumed the carbon intensity of the fuel mix to remain at the default value of 87.29 g CO_2e/MJ for the entirety of the simulation. In the ethanol push scenarios, the historical values were integrated into the simulation in 2012 and resulted in a slightly higher overall carbon intensity of the liquid fuel mix than is assumed in the provincial policies. After 2015, both ethanol push scenarios begin to show a decrease in the carbon intensity of the fuel mix, meeting the 10% reduction in carbon intensity goal by 2030—ten years later than the original 2020 deadline.

The carbon intensities of the fuel mix resulting from the two ethanol push scenarios begin to significantly deviate from one another at about the time of the second bioethanol plant's completion in 2028. Then, the increasing number of conventional vehicles in the Low EV scenario causes increased ethanol demand that cannot be met with domestic product, and thus higher carbon-intensity, imported ethanol must make up the difference. As the share of conventional vehicles in the light duty vehicle stock is significantly lower in the High EV scenario, ethanol production from British Columbia's forestry residues can more easily meet the demand, and after the completion of the third ethanol plant in 2037, lower-carbon, cellulosic ethanol makes up 100% of the ethanol demand until 2049, thus leading to a lower overall carbon intensity of the fuel mix. In table 4.11, one can see that by 2050, the 'Low EV + ethanol push' scenario leads to a 20% reduction in carbon intensity of the liquid fuel mix, while the 'High EV + ethanol push' scenario leads to a 25% reduction. While a 20 to 25% reduction in the carbon intensity of the gasoline-class fuel mix is good progress, it still leaves a lot of room for improvement, and further illustrates the challenges in developing truly low carbon light duty vehicle travel.

4.3.4 GHG emissions

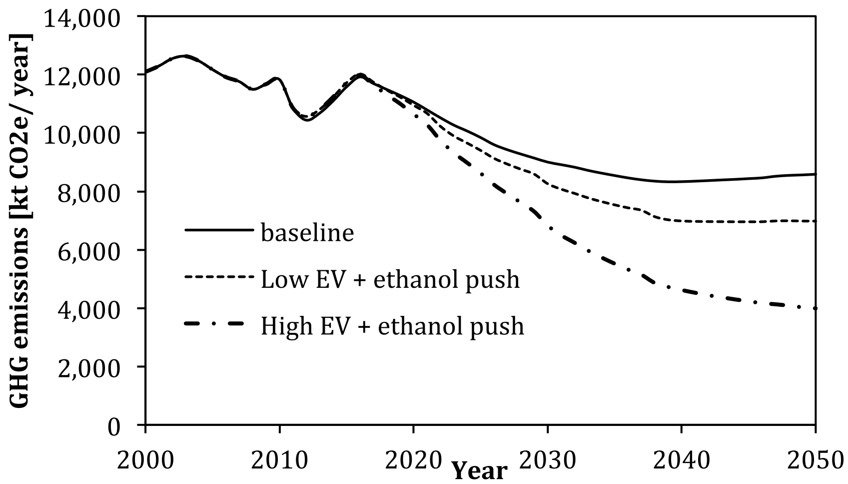


Figure 4.12 Annual GHG emissions from light duty vehicles under ethanol push scenarios and baseline scenario.

Table 4.12 GHG emissions from light duty vehicles in target years for baseline and two ethanol push scenarios [kt CO_2e]. Percent reduction from 2007 levels in 2050 calculated for reference.

Year	Baseline	Low EV + ethanol push	High EV + ethanol push
2007	11759	11759	11759
2015	11577	11718	11718
2020	11059	10948	10646
2050	8585	6980	3992
% reduction from 2007	27%	41%	66%

Using the carbon intensities of the fuel mix as a result of the two modelled ethanol push scenarios, the GHG emissions from light duty vehicle use were again calculated, and the results displayed in figure 4.12. Not surprisingly, the ‘High EV + ethanol push’ scenario offers markedly greater emissions reductions than the ‘Low EV + ethanol push’ scenario, due to not only lower carbon intensity of the gasoline-class fuel mix, but also less fuel consumption due to the higher share of electric vehicles on the road.

The resulting impacts on GHG emissions from light duty vehicle travel in target years are summarized in table 4.12. Compared to the baseline scenario, the ‘Low EV + ethanol push’ scenario results in an additional 14% in reductions from 2007 levels, showing a 41% overall reduction. When the ethanol push is combined with unconstrained EV growth in the ‘High EV + ethanol push’ scenario, the resulting decrease in carbon intensity of the fuel mix alongside the significant decrease in demand for liquid fuels results in a 66% reduction in emissions from 2007 levels, 54% lower than the baseline scenario.

4.4 Summary of GHG emissions in all modelled scenarios

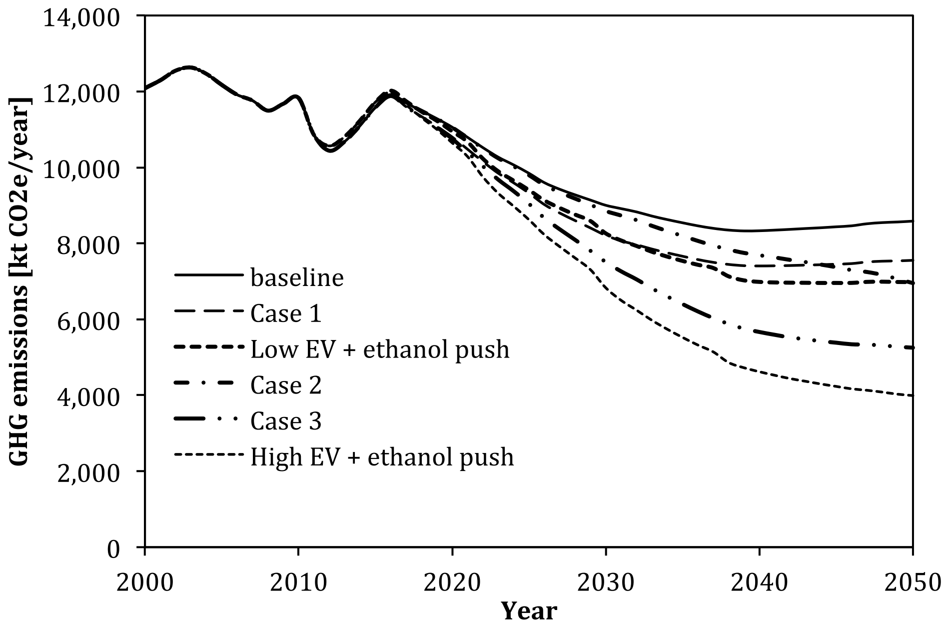


Figure 4.13 Annual GHG emissions from light duty vehicles for all modelled scenarios.

Table 4.13 GHG emissions from light duty vehicles and per cent reductions from 2007 levels in target years for all modelled scenarios.

Year	Baseline	Case 1	Case 2	Case 3	Low EV + ethanol push	High EV + ethanol push
Annual GHG emissions in target years [kt CO2e/year]						
2020	11059	10800	11051	10752	10948	10646
2050	8585	7553	6953	5252	6980	3992
Per cent reduction from 2007						
2020	6%	8%	6%	9%	7%	9%
2050	27%	36%	41%	55%	41%	66%

Annual GHG emissions from all the modelled scenarios can by seen in figure 4.13, with values from target years highlighted in table 4.13. Unsurprisingly the 'High EV + ethanol push' scenario resulted in the greatest reduction in GHG emissions—a 54% reduction from business as usual, and a 66% reduction from 2007 levels. The other scenarios represent a range of possible outcomes between business-as-usual (baseline) and deep reductions (High EV + ethanol push). Without an ethanol push, varying levels of EV adoption might cause between no reduction and 38% reduction from the baseline in 2050, while with the ethanol push we could see between 19% and 54% reduction from the baseline scenario.

4.5 Sensitivity analysis

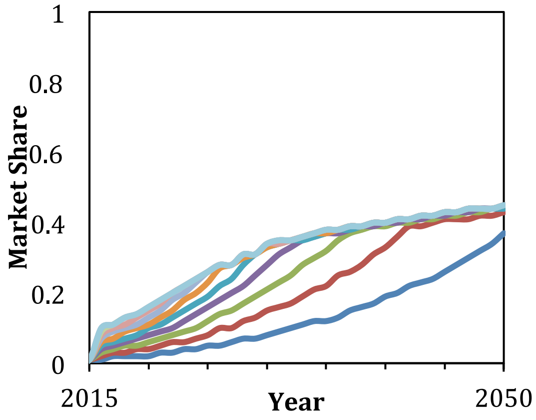
As the market penetration of EVs and the share of ethanol in the liquid fuel mix are the two focuses of this study, sensitivity analysis was conducted to check the sensitivity of these outcomes to incremental changes in the assumed parameters. The following summarizes the results of sensitivity analysis on key parameters impacting the EV market and the ethanol market.

4.5.1 EV market penetration

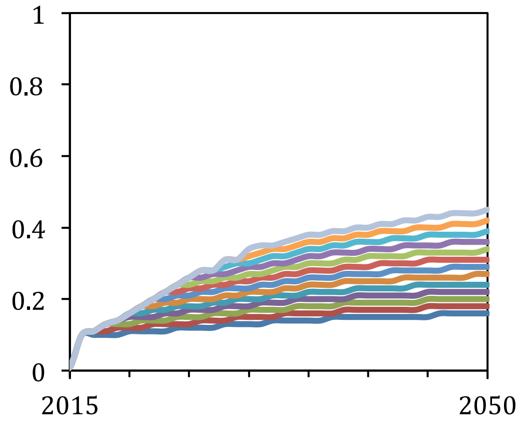
Figure 4.14 illustrates the results of the sensitivity analysis of EV market share to parameters that caused the widest range of outcomes. The three parameters to which the market share of EVs was most sensitive were our two main constraints—familiarity and availability—as well as the purchase price of EVs—the most highly weighted factor in the vehicle purchase decision process. Incremental changes in other factors (e.g. electricity and gas prices, charging time, charging infrastructure, etc.) showed a range of outcomes, but none as pronounced as the aforementioned three.

In figure 4.14.a, the bottommost line represents the EV market share with no availability constraints but at baseline familiarity level, or 14% of consumers in 2015 (as in Case 2 in section 4.3). The topmost line is the same as in Case 3, where familiarity and availability constraints are completely removed. As represented by the array of lines in the diagram, each 10% boost in familiarity causes the market share to more quickly reach its highest potential. The most pronounced is the initial 10% boost in familiarity, which causes the market share of EV to reach its top potential in 2041 instead of some time after 2050. After approximately 5 or more incremental increases in familiarity, the market share of EV appears to follow its unconstrained trajectory, implying that marketing efforts to increase familiarity with EVs could be very beneficial in early stages of promoting EV adoption, corresponding with the findings of Axsen et al. (2015).

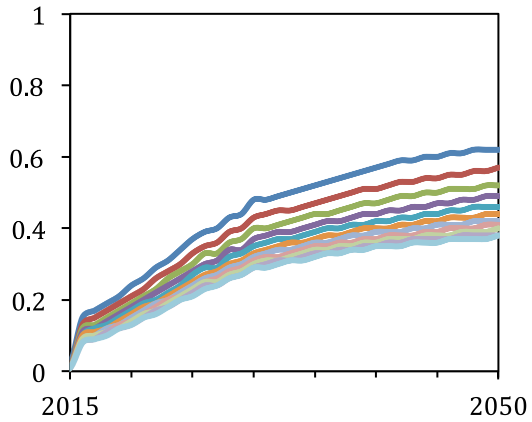
Figure 4.14.b, which shows the range of the EV market share due to incremental increases in vehicle variety, is fairly straightforward. If we assume 100% familiarity, then each model added to the EV market results in a 2-3% increase in the market share of EVs in 2050. Thus efforts to ensure that auto retailers stock and promote electric vehicles could be of utmost importance to widespread adoption.



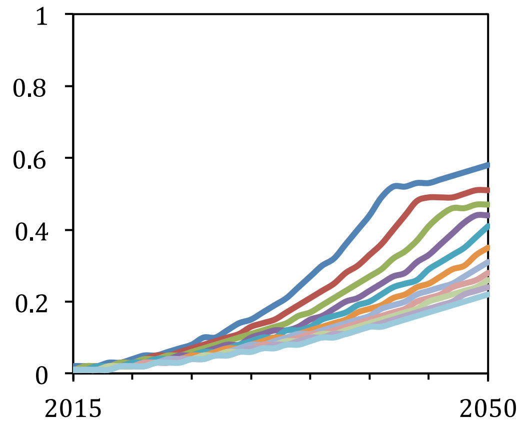
a. Consumer familiarity with EVs increasing by 10% increments; 20 EV models available



b. Available EV models increasing stepwise from 8 to 20; 100% consumer familiarity



c. EV purchase price incrementally rising from 0.2 to 3 times CV price; with no constraints

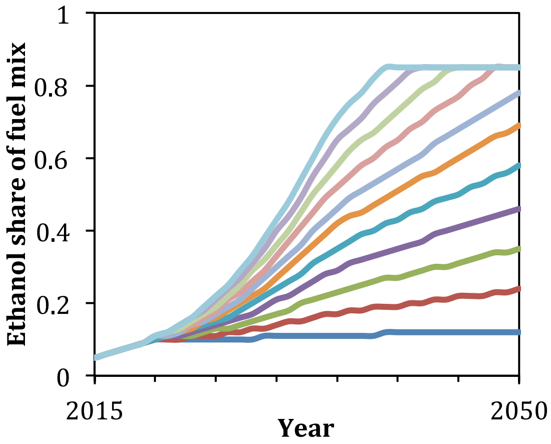


d. EV purchase price incrementally rising from 0.2 to 3 times CV price; constrained by familiarity

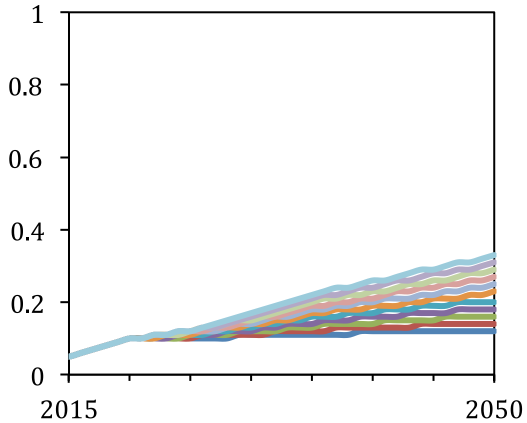
Figure 4.14 EV market share sensitivity to incremental changes in familiarity, variety, and purchase price.

Changes in the purchase price of an EV relative to a conventional vehicle were shown to have a significant impact on the EV market share between 2015 and 2050. In figure 4.14.c, when familiarity and availability constraints are removed, we can see that if an EV is priced at 20% that of a conventional vehicle, its market share approaches 61% in 2050 (the topmost curve in the figure), while incremental increases in EV price reduce the potential market shares down to 47% when the prices are equivalent, and 36% once the EV price is 3 times that of a conventional vehicle (the bottommost curve). In figure 4.14.d where sales are constrained by familiarity, incremental changes in the purchase price of an EV cause a range of outcomes from 56% to 22% market share in 2050, with a distribution similar to results in figure 4.16.c, and curves similar to those in figure 4.14.a. These results show that the purchase price of an EV relative to their conventional vehicle counterpart has a marked influence on the potential for sales. Thus intervention in the form of lowering EV prices or raising conventional vehicle prices could sway the market in electric vehicles' favour, as has been shown in the Norwegian vehicle market (Bjerkan et al., 2016).

4.5.2 Renewable content in the fuel mix



a. E85 install rate from 1 to 50 stations per year; flex fuel market share at 100% of conventional vehicles



b. Flex fuel market share increasing from 10% to 100%; E85 install rate constant at 10 per year

Figure 4.15 Renewable content in the liquid fuel mix sensitivity to E85 installation rate and market share of flex-fuel vehicles.

In figure 4.15.a we examine the share of ethanol in the annual liquid fuel consumption when E85 pump installation increases incrementally from 1 to 50 stations per year, and flex fuel vehicle market share is constant at 100% after 2020. Each increase in the installation rate causes increased share of ethanol in overall fuel sales, as we assume that consumers will choose E85 over the regular gasoline blend when given the choice between the two. Thus we see a range from 12% ethanol in the fuel mix by 2050, to 85% as early as 2039. Of course, increasing the installation rate even more would see 85% ethanol content in the fuel mix even sooner.

In figure 4.15.b, we assume that the installation rate for E85 infrastructure remains constant at 10 stations per year, but the flex fuel vehicle market share varies from 10% to 100% of sales in 2020 and thereafter. We see here a range of values between 12% and 33% for the share of ethanol in the fuel mix. In cases where the installation rate is greater, the same wedge shape would be seen as in figure 4.15.b, yet the uppermost bound would be higher. These figures further illustrate that a combination of high ethanol-gasoline blend accessibility *and* vehicle compatibility are necessary if ethanol is to take over a significant portion of the liquid fuel market.

5 Discussion

The following section discusses the results from the modelled scenarios and puts them into further context for British Columbia. Possible issues that might arise from the explored transition to a lower carbon transportation system are addressed here, as well as policy recommendations for how to foster the transition and overcome potential challenges. The section ends with a discussion of strengths and weaknesses of the model developed for this study, as well as opportunities for future research.

5.1 Overview of outcomes in 2050

From the outputs of the simulation in STELLA®, and based on our assumptions, it was found that unconstrained electric vehicle growth could lead to 1.46 million EVs on the road in 2050—making up 41% of the total light duty vehicle stock. However, considering constraints due to lack of variety and familiarity, the EV share of the vehicle stock in 2050 showed a range of values between 3% and 41%. When combining an ethanol push strategy with the highest and the lowest cases of EV adoption, we found that depending on the degree of market penetration of EVs, demand for ethanol in the remaining conventional vehicle stock could fall within the range of 0.6 to 1.0 billion litres per year while accounting for 32% of the liquid fuel mix in 2050.

The baseline scenario—in which EV market penetration was highly constrained and higher ethanol concentration in the fuel mix was not pursued—showed a reduction in well-to-wheel GHG emissions from light duty vehicles to 27% below 2007 levels in 2050. The reduction can mainly be attributed to improvements in the fuel efficiency of conventional vehicles. The High EV adoption scenario wherein electric vehicles made up 41% of the vehicles on the road in 2050 resulted in GHG emissions 39% below the baseline in 2050 (an overall 55% reduction from 2007 levels). An ethanol push strategy with baseline EV adoption resulted in a 19% reduction from the baseline in 2050, while combining the ethanol push with high EV adoption saw GHG emissions 54% below the baseline in 2050 (overall 66% below 2007 levels). Although a 66% reduction from 2007 levels is significant progress, it still results in an estimated 3992 kt CO_2e in emissions per year, which is mainly attributed to gasoline still being used in the majority of light duty vehicles. Based on these results, if the provincial government's target of an 80% reduction in GHG emissions across all sectors is to be achieved in 2050, then other sectors will have to make up for the shortcomings in the light duty vehicle transportation sector.

From the sensitivity analysis conducted, we found that the market share of electric vehicles was most sensitive to variations in consumer familiarity, available EV variety, and purchase price. The concentration of ethanol in the liquid fuel mix was most sensitive to E85 blender pump installation rate, and the market share of flex fuel vehicles in the annual conventional vehicle sales. These findings are reflected in the policy recommendations listed near the end of this chapter.

5.2 Energy demand in 2050

Comparing the annual energy demand in the baseline scenario to the high EV penetration (Case 3) scenario, it becomes quite apparent how much energy can be saved by transitioning to electric vehicles for private transportation. Electric vehicles are much more efficient than gasoline vehicles, as was discussed earlier, and based on factory measurements in todays vehicles, can show 69% higher efficiency than a comparably sized conventional gasoline vehicle (recall table 2.1). Based on our projections for the year 2050, operating the entire light duty vehicle fleet with only gasoline powered vehicles would consume 102 PJ of energy whereas an entire fleet of electric vehicles would consume 28 PJ—a 73% reduction in annual energy use for the exact same travel demand[1]. Regardless of potential for reducing greenhouse gas emissions, the energy savings alone could make EV worth pursuing, especially if the energy demand is met by renewable sources.

When considering ethanol as a means of offsetting gasoline consumption, no energy savings are offered. Since ethanol is burned in an internal combustion engine along with gasoline, it is subject to the same energy efficiency constraints as if pure gasoline were used. Furthermore, since ethanol has a lower energy density than gasoline, the volume of fuel required to meet the energy demand actually increases as ethanol content in the gasoline-class fuel mix increases. Ethanol does, however, offer the advantage of being compatible with modern internal combustion engines in low concentrations, and in higher concentrations in widely available flex-fuel engines. Plus ethanol has the ability to lower the carbon intensity of the liquid fuel mix used by conventional vehicles.

5.2.1 Electricity demand

Based on our assumptions for high electric vehicle growth, the number of EVs on the road in British Columbia in 2050 could reach almost 1.5 million vehicles. In this optimistic growth case, the total annual energy required to power the EV stock in 2050 would be 3200 GWh. The National Energy Board of Canada projects that electricity generation in British Columbia will reach 87,500 GWh per year in 2040 (NEB, 2016). If we assume that level of generation persists until 2050, then the total EV stock would require less than 4% of the annual electricity supply. Although it appears the amount of electricity generation in British Columbia could easily support an EV stock that makes up over 41% of the light-duty vehicles, issues may arise with how and when battery charging takes place.

Charging an EV battery may be done in a number of ways. Level 1 charging involves plugging the vehicle into a regular 120-volt electrical socket (like one would a vacuum cleaner) and requires 1.8 kW of power (Yilmaz & Krein, 2013) which would take over 16 hours to charge a typical 30 kWh battery. Level 2 charging involves plugging in to a 240-volt socket (i.e. a dryer plug) and depending on the EV could require between 3.3 and 10 kW of power (Yilmaz & Krein, 2013)—resulting in a full charge in 3 to 10 hours for a 30 kWh battery. Finally, Level 3, or DC fast charging (found in Tesla's Super Charger stations) uses 90 kW of power (Dong et al., 2014) and can charge a fully depleted 30 kWh

[1] Note that these figures represent a reduction in *end-use* energy, and do not account for energy required in the production of electricity. However, this is not so important in British Columbia where most of the electricity is produced by hydroelectric generation, which is a relatively efficient process with few associated GHG emissions.

battery in about 20 minutes, but their purchase is well outside the price range for most mainstream vehicle consumers.

For daily electric vehicle use, level 2 charging capability at home is often considered a necessity to EV consumers (Axsen & Kurani, 2012). If we assume that in 2050, when the EV stock could potentially have reached 1.46 million vehicles, everyone has access to level 2 charging, then what would happen if all 1.46 million electric vehicle owners plugged in their vehicles to charge at the same time?

Assuming that by 2050 each charger uses 10 kW of power and assuming no measures are taken to redistribute the electricity demand, then the resulting demand is 14,600 MW of power. Electricity generation capacity, or the amount of electricity that can be supplied at a given moment, in British Columbia is projected to be approximately 21,000 MW after 2040 (NEB, 2016). So uncontrolled, or unregulated charging of that many EVs in British Columbia could create demand for up to 71% of the total electricity generation capacity of the province. This could cause major issues for the existing electricity supply system such as overloading the grid and causing blackouts, damaging grid infrastructure, or requiring the development of large and costly electricity generation projects to increase capacity (Mwasilu et al., 2014). Thus if EVs are to capture a large portion of the vehicle market, measures will need to be taken to deal with the increased electricity demand especially during peak charging hours.

Integrating a ‘smart grid’ system that allows for communication between EVs and the electricity grid could help to manage the increased load demand from EV charging (Waraich et al., 2013). By monitoring the demand from EV charging and incorporating the data into supply-side measures, a more robust strategy can be developed that matches supply to the increased demand. Battery charging for an individual EV may be stopped or its intensity decreased during peak hours by communication between the smart grid and the charging technology (Waraich et al., 2013).

Another strategy involves using vehicle to grid (V2G) technology wherein EVs that are plugged into the electricity grid act as an extension of the grid and electricity can flow from a vehicle battery *back into* the grid when electricity demand is high, or from the grid into the battery, as in typical charging (Mwasilu et al., 2014). In this manner, many EVs connected to the electricity grid can help to stabilize the system and provide more capacity during peak load hours. Vehicle to grid systems could also help to provide additional storage for renewable energy systems such as solar or wind power that would benefit from the added storage provided by EV batteries (Mwasilu et al., 2014). Agreements could be reached between EV owners and utility companies wherein owners are compensated for energy flowing back into the grid from the electric vehicle batteries (Waraich et al., 2013).

The feasibility of establishing an electricity demand-and-supply management system in British Columbia, such as vehicle-to-grid, is beyond the scope of this study. However, if widespread EV adoption is to occur, robust evaluation of measures to control the increase in electricity demand, especially during peak hours will be necessary.

5.2.2 Ethanol demand

We examined a scenario in which three cellulosic ethanol plants were constructed in British Columbia, with a combined production capacity of 0.6 billion litres of ethanol per year. This was enough to cover the annual ethanol demand from about 2 million conventional vehicles running on a fuel mix with an average of 32% ethanol content by volume. These 2 million vehicles were the remaining conventional vehicle stock after EVs captured 41% of the on-road stock in 2050. If all of these 2 million vehicles were to run on an 85% ethanol-gasoline blend, the annual demand for ethanol would be 2 billion litres.

In our lowest EV growth (baseline) scenario the ethanol demand would reach 3.3 billion litres in 2050 if all conventional vehicles operated on E85. As a point of comparison, all of Canada consumed 2.7 billion litres of ethanol in 2015, 1.7 billion litres of which was produced domestically (USDA Foreign Agricultural Service, 2015). Although British Columbians make up approximately 13% of the total population of Canada, the demand for ethanol from BC's vehicle stock could strongly alter the Canadian biofuel market by greatly exceeding the national supply and consumption of ethanol. Among the literature reviewed, the highest estimate of bioethanol production from forest residues in British Columbia was 3.1 billion litres per year (Yemshanov et al., 2014), which could almost completely cover the demand in 2050 for E85 if no alternative fuel vehicles take over a significant portion of the light duty vehicle market, and thus a self sustaining ethanol market could potentially be reached. However, we did not choose to pursue this outcome in the scope of this study.

We decided on the construction of only three cellulosic bioethanol plants in British Columbia, each with an annual production capacity of 200 million litres per year, as this seemed a realistic goal given the timeframe considered and the range of estimates for production capacity in the literature reviewed. Therefore this was the strategy explored in the 'ethanol push' scenario, along with E85 pump installation and market penetration of flex-fuel vehicles described in section 4.3. Also, we wanted to explore a scenario where all ethanol demand was met with cellulosic ethanol produced from British Columbia's forestry residues, and thus combining the ethanol push with high EV market penetration provided the ability of local production to meet nearly all of the projected annual ethanol demand from conventional vehicles in 2050 based on our assumptions.

Establishing an ethanol production industry in British Columbia would be a major industrial and economic endeavour. Froese et al. (2008) places the upfront investment cost for a cellulosic bioethanol plant that processes 770,000 dry tons of woody biomass per year, or 92 – 231 litres of ethanol (Mabee & Saddler, 2010), at $224 million (in 2005 US $) plus operation and maintenance costs between $48 and $61 million per year. Converting to present day Canadian dollars puts the capital investment for three biofuel plants at over $1 billion plus operation and maintenance. Further investment would also be necessary in the installation of blender pumps in gas stations, which could require significant subsidies to reach the over 2000 gasoline retailers in the province.

If an ethanol industry were to be pursued, significant planning and assessment of the future of transportation fuels would be absolutely necessary. In the case that domestic ethanol production is developed in British Columbia, the province would benefit from having its own supply of renewable fuel and thus be less subject to uncertainties inherent in reliance on imports. However, the ethanol produced would have to remain competitive in price with imported ethanol in order to maintain presence in the marketplace. Further assessment of the economic aspects of establishing a cellulosic ethanol industry in British Columbia is left to future research.

5.2.3 Gasoline demand

In our most optimistic scenario, where electric vehicles make up 41% of the light duty vehicle stock, and ethanol makes up 32% of the liquid fuel mix in 2050, there is still demand for 1.3 billion litres of gasoline per year for the light duty vehicle stock. Even if 100% of the conventional vehicles manage to be fuelled with E85, more than 350 million litres of gasoline would still be required each year to cover the 15% gasoline content in the fuel mix. To realize truly deep reductions in GHG emissions from light duty vehicle use, the demand for gasoline should be removed entirely. Therefore alternative fuel technologies that were mentioned earlier but not discussed in detail (e.g. biodiesel, drop-in biofuels, hydrogen fuel cells) will likely be required along with electric vehicles and bioethanol if gasoline demand is to be offset entirely. Only once gasoline is removed from the fuel mix can carbon neutrality be approached in the light duty vehicle transportation sector.

5.3 EV batteries

5.3.1 Battery life and replacement

An important factor that can play not only an important role in the environmental impact of EVs, but also their attractiveness relative to conventional vehicles is the battery lifetime. In the model, we assumed a battery lifetime of 8 years, versus a vehicle lifetime of 16 years, and battery replacement cost was included in the lifetime operating costs of an EV. However, simply quantifying battery lifetime as a number of years neglects many variables.

Over time, and with increased use and number of charges, a battery will lose its storage capacity causing the vehicle's driving range to decline (Saxena et al., 2015). The rate of degradation of a battery depends on how frequently it is charged, the depth of discharge (how much charge was expended between charges), and the strength of charging (Peterson et al., 2010). Typically a decrease to 70 – 80% of original capacity is considered as sufficient criteria to replace the battery, which can occur after several thousand charges (Wood et al., 2011). A recent study, however, finds that concerns over battery degradation may be exaggerated. Saxena et al. (2015) found that a battery that is reduced to 80% of its original storage can still meet the demands of most EV drivers. Even at 30% storage capacity, more than 55% of U.S. drivers' everyday needs could be met with just level one charging (regular wall plug) access at home and work. A limiting factor could be the demand from unexpected long trips, nevertheless Saxena et al. (2015) argue that the retirement criteria for batteries should be adjusted to account for these findings.

Concerns also exist over vehicle-to-grid systems, and how adding many small charges and discharges to the battery might affect its lifetime. However, Peterson et al. (2010) found that when compared to charging demand from driving use, vehicle-to-grid demands on the battery caused half the capacity loss per unit of energy charged. Furthermore after a simulation of several thousands of driving-days worth of vehicle-to-grid demand, a lithium-ion battery showed less than 10% capacity loss (Peterson et al., 2010). Therefore, demand for battery replacements may not be as significant as is often assumed.

5.3.2 Resource demand from EV battery production

In our high EV growth scenario, EVs made up 45% of the annual light duty vehicle sales by 2050, which translates to around 100 thousand new EVs purchased per year and thus requires the production of 100 thousand EV batteries, not counting replacement batteries. The province of British Columbia is not an isolated system, and therefore if EV adoption is high there, it is likely high elsewhere, and the significant demand for resources from the production of batteries should be strongly considered. Although outside the scope of BC's goals (and similarly outside the scope of this study), the ability of global reserves to meet resource demand for future EV battery production deserves a brief discussion.

Depending on the battery type used in future electric vehicles, demand for metals including lithium, nickel, cobalt, vanadium, cadmium, lead, and rare-earth elements come under discussion for their ability to meet the demand from increasing battery production (Andersson & Råde, 2001). Currently the most prominent battery type for EVs is the lithium-ion battery, and it is likely to persist as the battery of choice for the foreseeable future (Speirs et al., 2014). As the lithium for the batteries must be extracted from natural reserves in order to keep up with EV demand, there is great debate concerning the ability of lithium resources and production to meet the increase in demand. In an outlook where full battery EVs and plug-in hybrid EVs combine to reach 109 million sales per year worldwide in 2050 (as part of a trajectory to decrease global transportation emissions by 50%), then based on average battery size in today's vehicles, the lithium demand from battery production could reach 989 thousand tons per year—nearly 9 times the high estimate for production in 2020, but the authors conclude that based on recent rapid growth in lithium production, meeting the demand in 2050 is plausible (Speirs et al., 2014).

Lithium is discussed here as an example of a resource that can potentially limit the production of EV batteries. However, robust evaluation of all the resources required to meet battery production is necessary if EVs are to move forward as a prominent alternative to fossil fuel powered vehicles.

5.4 Policy recommendations

Based on systems analysis of the literature reviewed, modelled scenarios to 2050, and sensitivity analysis results, we arrived at the following policy recommendations to the British Columbia provincial government should they choose to pursue electric vehicles or ethanol fuel as means of reducing GHG emissions from light duty vehicles.

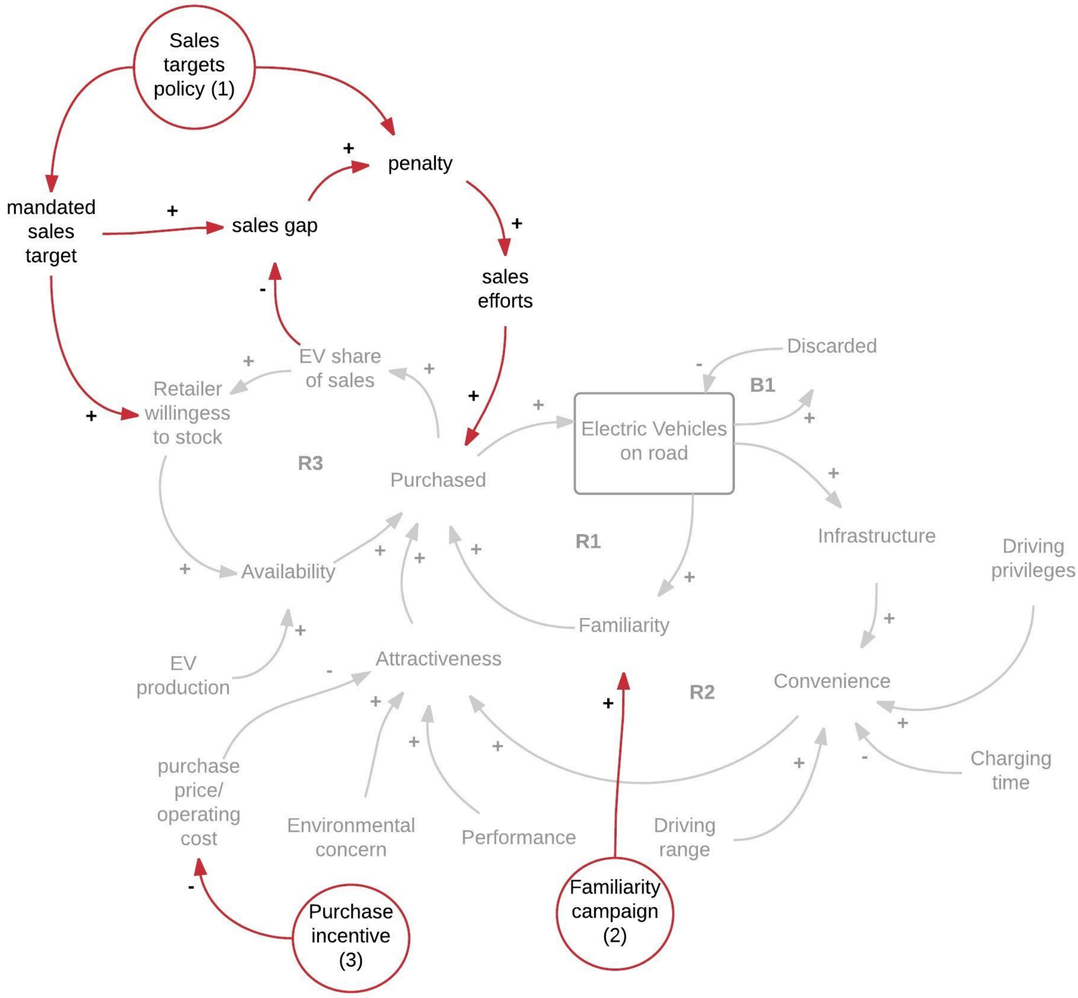


Figure 5.1 Causal loop diagram of the electric vehicle market in grey (from figure 3.3) with policy intervention points added in red.

Figure 5.1 revisits the casual loop diagram of the electric vehicle market as described in section 3.3, and adds three policy actions, each targeting one of the reinforcing loops that impact EV adoption. Many policy actions were considered, but the three highlighted in figure 5.1 and explained below were determined to have the most significant impact on EV adoption.

1. *Introduce and enforce sales targets for zero-emission light duty vehicles.*

In strong agreement with the Climate Leadership Team's (2015) recommendation to the provincial government, we support the following sales targets for zero-emission vehicles:

10% of new vehicle sales by 2020, 25% by 2025, and 30% by 2030. Dealerships could be held accountable for their own sales, paying a penalty for non-compliance; or zero-emission vehicle credits could be bought and sold between dealerships in order to ensure the quotas are met. Depicted in figure 5.1, this policy targets reinforcing loop R3, the supply-side or dealership side of EV adoption. This policy can help to ensure that new EVs or other zero-emission vehicles are given sufficient visibility in the early stages of their adoption, while being made readily available to the consumer and presented as a viable vehicle option.

2. *Invest in campaigns to boost consumer familiarity with electric vehicles.*

Sensitivity analysis of our model revealed that annual EV sales were very sensitive to consumer familiarity with electric vehicles. Importance must be placed on increasing the public's familiarity with electric vehicles and their operation, so that they are willing to consider an electric vehicle as a potential next vehicle (see in figure 5.1 where a familiarity campaign targets reinforcing loop R1). Advertising the merits of electric vehicle use (e.g. fuel cost savings, low emissions, access to restricted vehicle lanes) can help to draw attention towards EVs and increase interest. Also, informing the public that an electric vehicle can meet daily driving demands is essential.

3. *Extend the timeframe for purchase incentives towards electric vehicles to at least 2019.*

Herein we target reinforcing loop R2 in figure 5.1 by lowering the purchase price of EVs and thus making them more economically attractive. Not only does lowering the purchase price of EVs make them more competitive with conventional vehicles, but it can also increase awareness of electric vehicles. The longer the incentives are in place, the more opportunities there are for new vehicle purchasers to take advantage of the savings. Thus this recommendation works in close conjunction with the previous two recommendations by not only increasing the potential for sales, but by increasing awareness through promoting the purchase incentives and word-of-mouth advertising.

4. *Conduct robust evaluation on the impact of added electricity demand from widespread electric vehicle adoption and develop sound strategies for meeting the demand.*

If electric vehicles capture a significant portion of the market, the provincial government and utilities companies must be sufficiently prepared to meet the added electricity demand. Thus proper evaluation of supply-side and demand-side measures must be conducted in a timely fashion in order to avoid complications from mass electric vehicle charging.

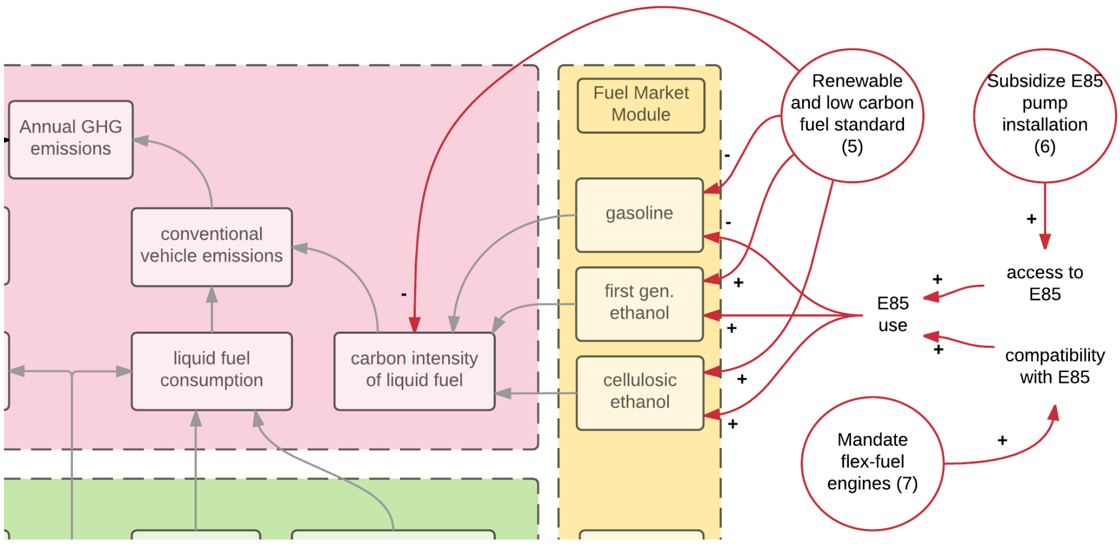


Figure 5.2 Policy intervention points added to the fuel market module from figure 3.2.

Figure 5.2 depicts policy intervention applied to the GHG emission flow chart described in section 3.1. The policy actions—depicted here and outlined in the following text— work to lower the carbon intensity of the gasoline-class fuel mix by increasing the share of ethanol in the fuel pool.

5. *Raise renewable fuel standard to a minimum of 10% renewable content in the gasoline-class fuel mix by 2020, and extend the low carbon fuel target to a 20% reduction in carbon intensity of fuel mix by 2030.*

Offsetting gasoline use is essential for reducing greenhouse gas emissions. Not only is it important to offset gasoline with renewable resources, but it is also important that renewable fuels are pursued that are as close to carbon neutral as possible. By placing pressure on retailers with more stringent regulations from the Renewable and Low Carbon Fuel Requirements, the fuel market can be shifted to favour low carbon renewable fuels over fossil fuels for transportation.

6. *Subsidize installation of ethanol blender pumps and ensure E85 is priced according to its lower energy density when compared with gasoline.*

Currently, engine compatibility with high ethanol-gasoline blends far outweighs access to these blends. As flex-fuel vehicles penetrate the market their potential to reduce gasoline demand can only be realized if high-ethanol blends are made widely available. Subsidizing the installation of ethanol blender pumps can aid in improving access to E85 and establishing high-ethanol blends as a commonplace fuel. Advertising ethanol at a lower price per litre than gasoline may also increase its attractiveness, even if the price per unit of energy is equivalent to that of gasoline.

7. *Mandate a high percentage of flex-fuel engines in new conventional vehicle models.*

While currently compatibility with E85 exceeds access to E85, the two will need to increase together in order to maximize the uptake of E85 as a transportation fuel. Mandating flex-fuel engines from automobile manufacturers can help to ensure that large numbers of conventional vehicle owners are able to use high-ethanol blends as they become available.

8. *Conduct a robust assessment of potential biofuel production from forestry residues in British Columbia in order to determine viability as an industry.*

Cellulosic bioethanol production from forestry residues shows potential as a resource for low-carbon renewable fuel in British Columbia. However, due to limits to the scope of this study, we were unable to assess the viability of establishing cellulosic ethanol production in British Columbia. Therefore we recommend that further, more robust measures be taken to assess the potential for biofuel development from BC's forestry residues.

5.5 Comments on the model

The model developed for the purpose of this study is a highly aggregated and simplified representation of the light duty vehicle market in British Columbia, as well as the composition of the fuel supply in the province. In building the model with the intent of forecasting the greenhouse gas emissions embodied in light duty vehicle transportation in 2050, many assumptions were made based on a wide variety of sources. The following discusses the various strengths and weaknesses associated with the model developed here, as well as those of the assumptions used in the simulations.

The main advantages of the model stem from its applicability and simplicity. The computer model very closely resembles the conceptual model used for its construction. Even without number values, one can rationalize the feedback effects inherent in the system just by observing the causal loop diagrams shown in chapter 3. Once these causal relationships are converted into a mathematical computer model in STELLA®, its small size and visual layout allows for plenty of experimentation and on-the-fly adjustments. As argued in the verification (section 3.8), the modelled output for GHG emissions from 2000 to 2013 produced a satisfactory estimate of historical values that explains 78% of the variation in annual emissions ($r^2 = 0.78$). Thus we are satisfied with its ability to simulate realistic GHG emission levels from light duty vehicle travel resulting from our assumptions.

5.5.1 The electric vehicle market

By dividing the vehicle stock into just two main vehicle types, electric and conventional, we were able to isolate the main points of competition between the two vehicle types and address those to measure sensitivity to potential changes in the system. However, because we assume just two vehicle types, competition between EVs and other alternative fuel vehicles (e.g. plug-in hybrids, hybrids, fuel cells, biodiesel, etc.) are not directly addressed. It could be argued, though, that these alternatives are to an extent represented in the overall fuel efficiency of the conventional vehicle fleet that we assumed to meet the U.S. Corporate Average Fuel Economy standards by some arbitrary means. Any improvements in the fuel efficiency of the non-EV fleet may arise from adoption of non-EV alternative fuel vehicles and not just from changes in gasoline conventional vehicle technology.

Also, the model assumes homogeneity over the entire province, as if the entire population were likeminded individuals living in one confined city. This is, of course, not the case in reality. British Columbia is a very large land area, quite sparsely populated, and with diverse communities that may exhibit many different light duty vehicle needs. However, the majority of its population live in major urban centres (e.g. almost two-thirds of the population live in the two most populous urban centres alone, Vancouver and Victoria (BC Stats, 2015a)). Thus we assume that our model is applicable to the majority of the light duty vehicle users in the province.

Furthermore, a lot of weight was placed on factors that we assumed to be exogenous. For example, vehicle purchase prices and fuels costs, technological advances, and vehicle variety were assumed to progress along a trajectory that was unaffected by market activities in British Columbia. As the light duty vehicle market in the province is projected to consist of over 200 thousand annual sales by 2050, this could have significant influence on the aforementioned factors. Thus a model that has greater consideration of endogenous change might exhibit greater predictive power than the model constructed for this study.

The forecasts for potential market share of EVs in 2050 produced in this simulation are not claimed to be a prediction of the future, but are simply potential outcomes based on our assumptions. The results can be compared to other studies on EV market penetration. For example, Axsen et al. (2015) project the market share of plug-in electric vehicles (EV and plug-in hybrid electric vehicles) in British Columbia to be between 1% and 32% of sales in 2020 depending on various constraints. Shafiei et al. (2012) simulated a favourable scenario in Iceland where EV sales could make up the entire light duty vehicle market by 2030. Shepherd et al. (2012) modelled a range of scenarios that could see EV and plug-in hybrid electric vehicles combine to capture between 40 – 58% of the vehicle market in the U.K. by 2050. For further reference, Al-Alawi and Bradley (2013) have compiled a comprehensive review of hybrid, plug-in hybrid, and electric vehicle market modelling studies conducted up to 2012, and offer valuable insights into the strengths and weaknesses of the studies.

5.5.2 The fuel market

It should be reemphasized here that the fuel market was not modelled as a dynamic system. The incorporation of ethanol into the liquid fuel mix was determined at the onset of the simulations, and relied on the set rates of E85 installation in gas stations, and market share of flex fuel vehicles—both of which were exogenous variables. The intention behind this portion of the model was to observe the diffusion rate of high ethanol blends through the conventional vehicle stock in the absence of price, preference, and supply constraints. Our only concern was to measure ethanol's potential share of the annual fuel sales under the two assumed scenarios, and the resultant impact on the carbon intensity of the liquid fuel mix. Further research is necessary to assess the competiveness of ethanol with gasoline and other fuels following the market structures in place in British Columbia.

5.5.3 Greenhouse gas emissions

As stated before, the greenhouse gas emissions in each year were calculated as the product of total energy use and the carbon intensity of the energy used for each vehicle type. For the fuels consumed, we assumed that all four fuel types considered—electricity, gasoline, first-generation ethanol, and cellulosic ethanol—maintained constant carbon intensities throughout the simulation. It was also assumed that any ethanol coming from outside of British Columbia had the carbon intensity of first-generation ethanol. Realistically, the carbon intensities of the fuel supplies will vary from year to year. For example the BC Ministry of Energy and Mines (2013) published a list of approved lifetime carbon intensities for biofuels used in the province, and showed a range from -4.23 to 70.36 g CO_2e/MJ for ethanol depending on the supplier. Gasoline's carbon intensity, too, will vary depending on the production practices (Melaina & Webster, 2011). Carbon intensity of electricity could also change if more generation projects are constructed to keep up with demand from electric vehicles. Consideration of these variables was outside the scope of this study, but a more robust model might include endogenous changes in the carbon intensities of fuels consumed.

5.6 Opportunities for further research

Future research may be conducted to incorporate competition not only between conventional vehicles and alternative fuel vehicles, but also within alternative fuel vehicles themselves. Comparisons could then be drawn between the relative penetration capabilities of specific technologies, as well as a more robust evaluation of the potential to completely phase out gasoline-fuelled vehicles. Furthermore, as this study used publically available aggregated data over the entire province, further work could be conducted to include regionalized data into the model to reflect the travel needs and vehicle requirements in differing communities.

The model, and associated projections, could also greatly benefit from the inclusion of endogenous change in the fuel market. Further research to create a dynamic model of competing fuel types in the provincial fuel market would serve to help isolate necessary intervention points in order for biofuels and electricity to outcompete gasoline consumption.

6 Conclusion

Combining electric vehicle adoption with an ethanol push strategy showed potential for reducing greenhouse gas emissions from light duty vehicles to 54% below a business-as-usual scenario in 2050, translating to a 66% reduction from 2007 levels. However, impediments exist that could significantly hinder progress towards this outcome.

In order to realize a high potential for EV adoption, initiatives must be taken to increase consumer familiarity with EVs, and to ensure the availability of a wide range of EV model options. A combination of advertising campaigns, minimum sales targets, and purchase incentives for EVs can make them more competitive with conventional vehicles, as well as increase their visibility and ensure their availability for purchase.

If conventional internal combustion engine vehicles persist as a prominent light duty vehicle choice, incorporating biofuels into the liquid fuel mix will be essential for lowering GHG emissions from light duty vehicle travel. Increasing the concentration of ethanol in the gasoline-class fuel mix can offset gasoline sales, but will only significantly reduce emissions if low-carbon ethanol resources are utilized. Exploring the option of cellulosic bioethanol production from British Columbia's forestry residues shows its potential as a resource for low-carbon ethanol as well as a new industry for British Columbia. However, significant investment would be required to upstart production and to make high ethanol blends not only available to flex-fuel vehicle owners, but also competitive with gasoline prices. Furthermore, based on flex-fuel engine technology, the fuel mix must maintain a minimum of 15% gasoline by volume in order to operate properly. Thus without development of a viable drop-in gasoline substitute, conventional vehicles will continue to consume fossil fuels.

The results here are not claimed to represent the future of light duty vehicle use in British Columbia, but they do explore a scenario where electric vehicles can capture a significant portion of the market, and domestic cellulosic ethanol production can supply almost one third of the annual liquid fuel demand from light duty vehicles. Further research is required to explore a scenario where gasoline use is offset entirely, and greenhouse gas emissions from light duty vehicle travel sees even deeper reductions.

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Appendix A: STELLA® Model

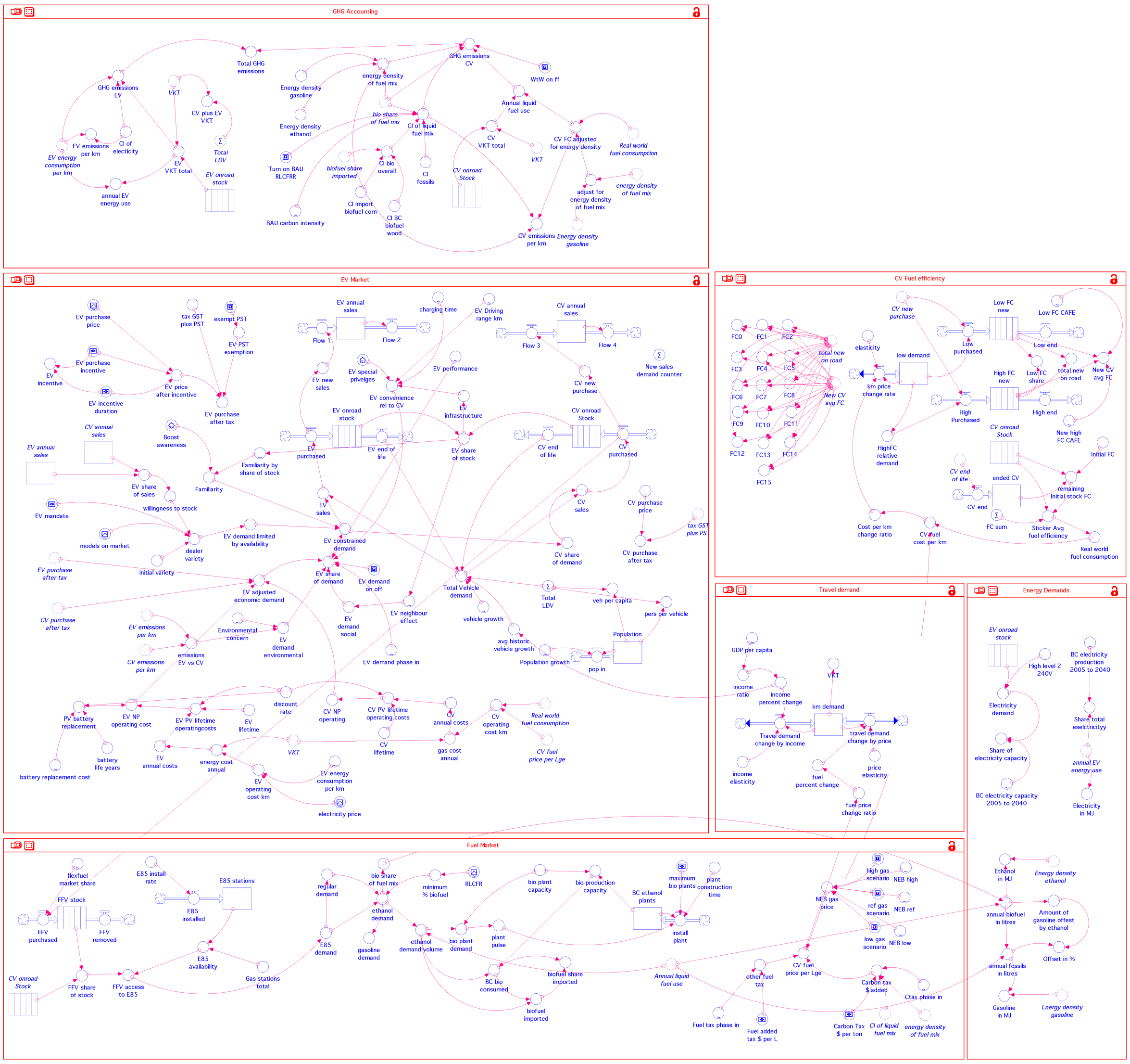


Figure A.1. Image of the STELLA® model. Modules counter clockwise from the top: GHG accounting, vehicle market, fuel market, energy demand, travel demand, conventional vehicle fuel efficiency.

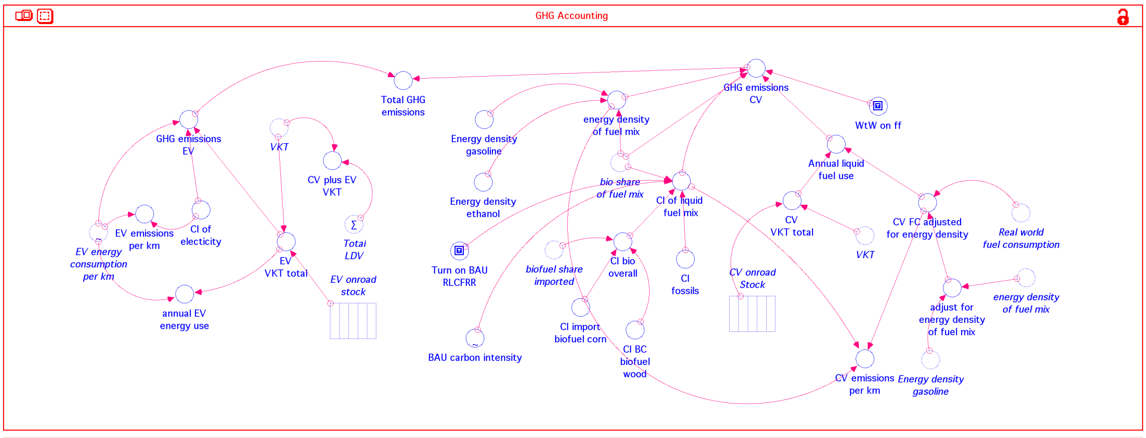


Figure A.2. Close up of GHG accounting module.

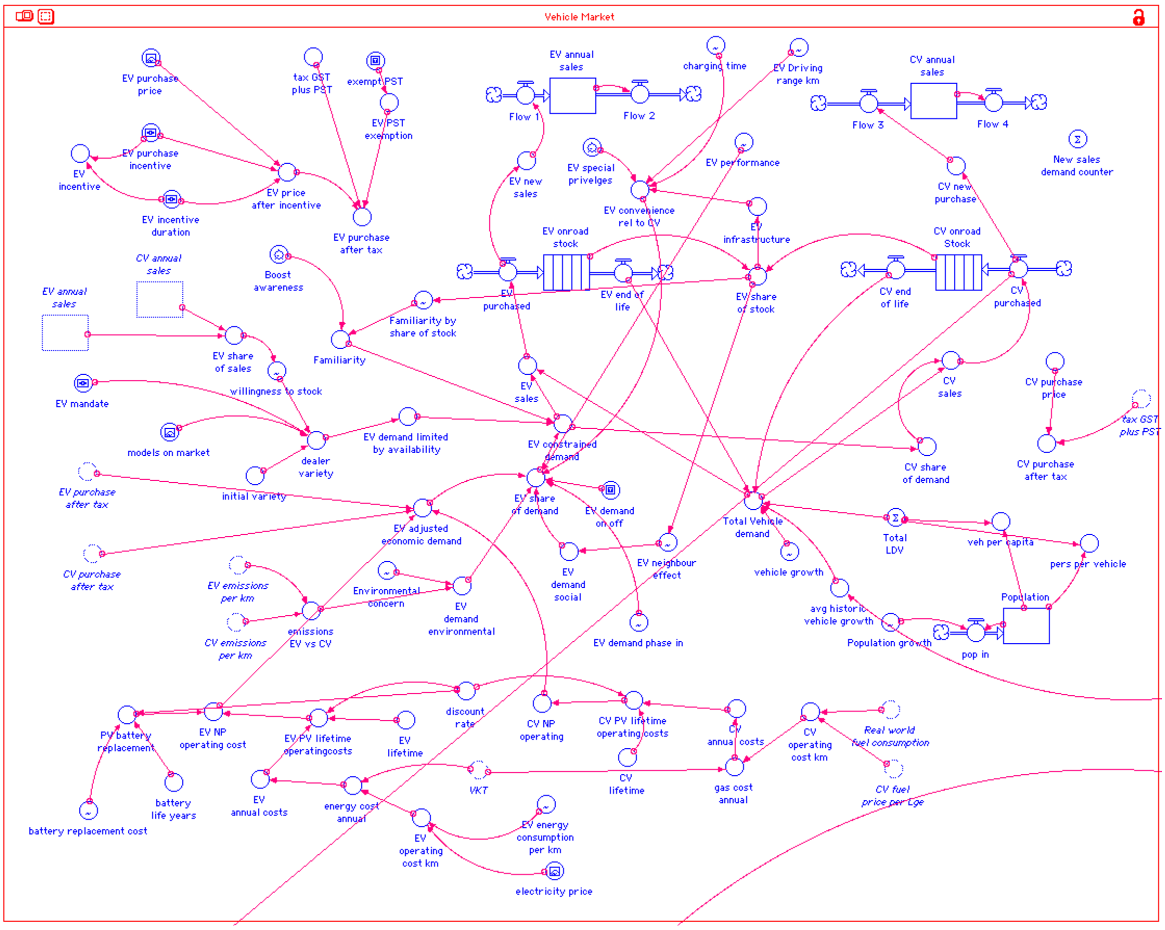


Figure A.3. Close up of vehicle market module.

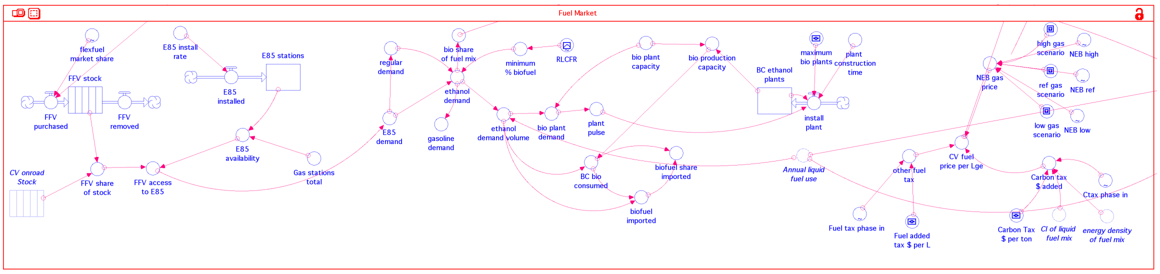


Figure A.4. Close up of fuel market module.

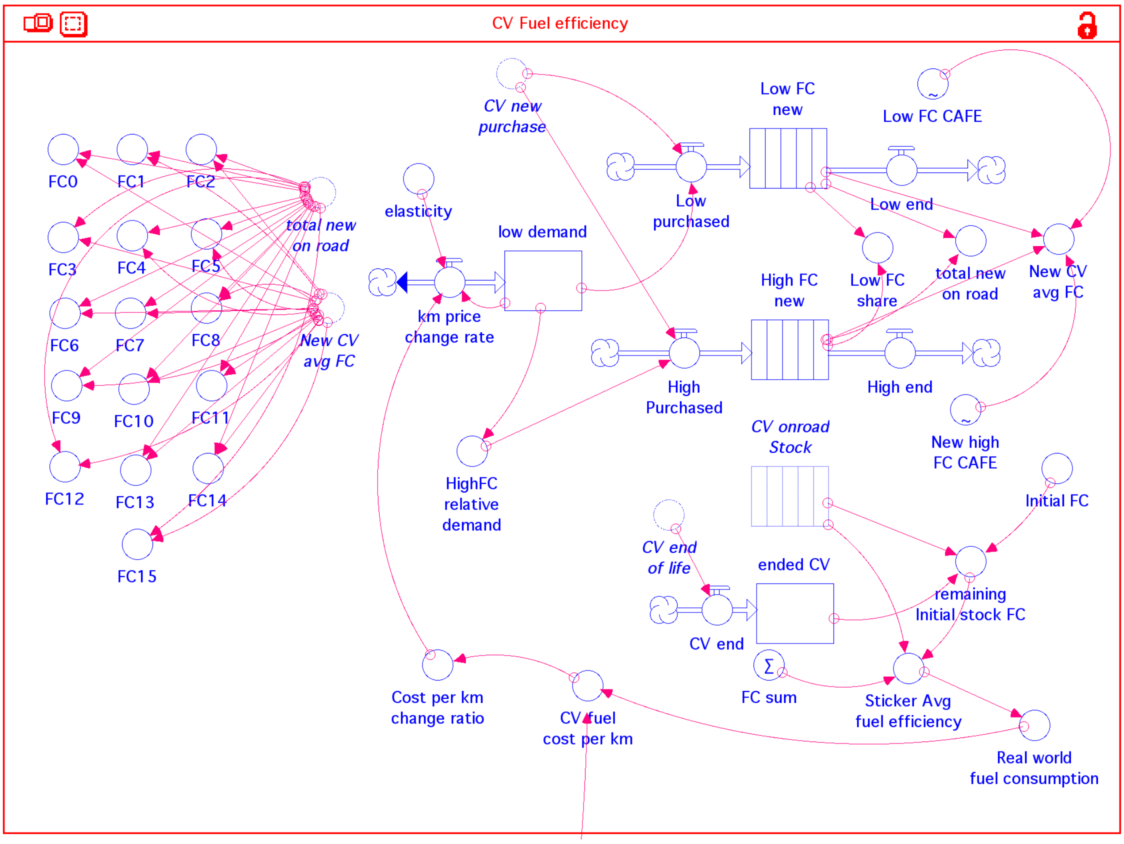


Figure A.5. Close up of fuel efficiency module for conventional vehicles.

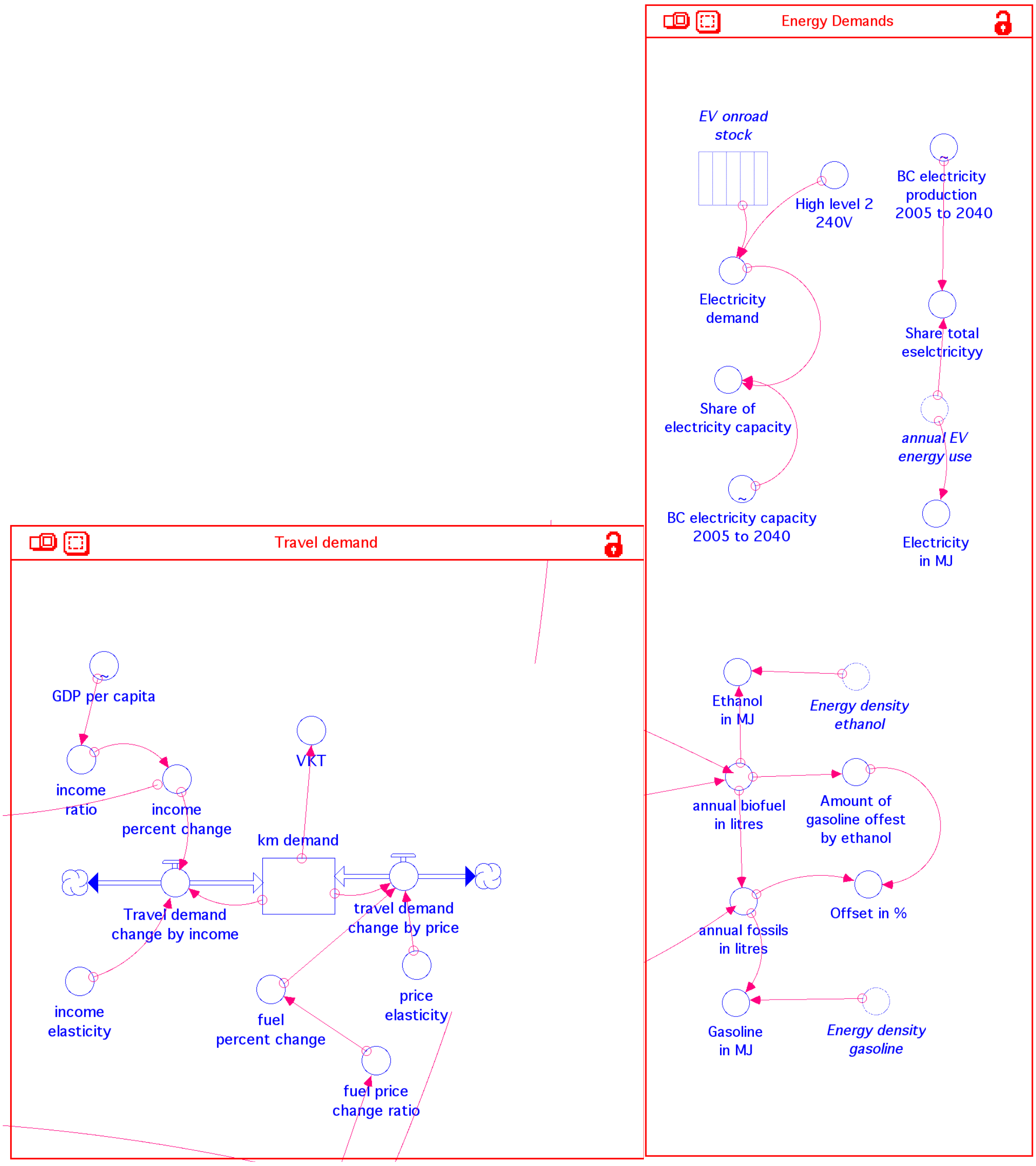
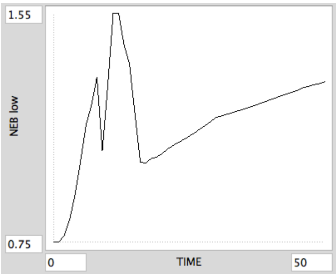


Figure A.6. Close up of travel demand module and energy demand.

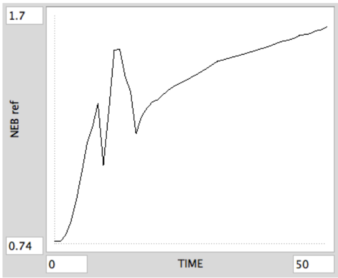
Appendix B: Graphical assumptions

Time dependent curves and feedback curves in STELLA® model

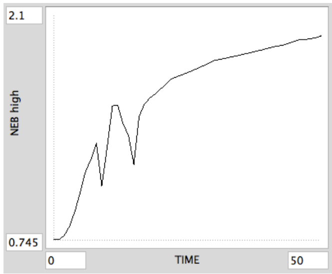
Travel demand module



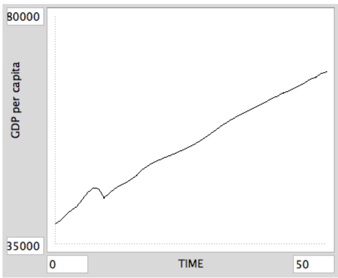
a. Low gas price scenario ($/litre)



b. Reference gas price scenario ($/litre)



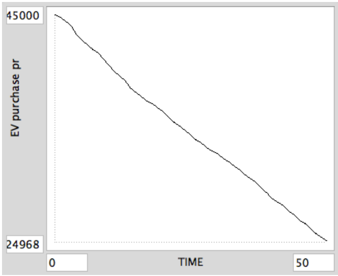
c. High gas price scenario ($/litre)



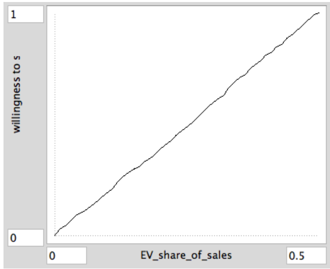
d. GDP per capita

Figure B.1. Historic and projected retail prices for gasoline (high, low, and reference cases) and GDP per person (2007 Canadian $) from 2000 to 2050 based on National Energy Board of Canada: Canada's energy future (NEB, 2016).

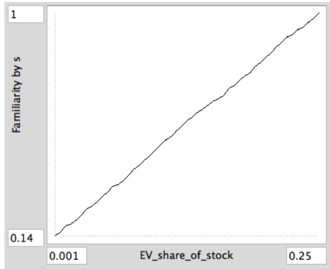
Vehicle market module



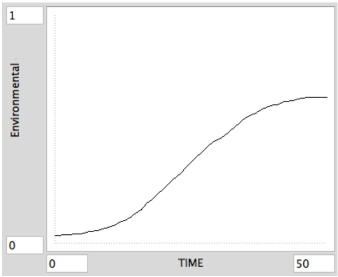
a. EV purchase price



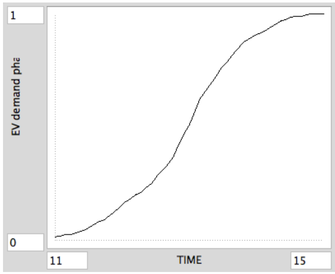
b. Dealer's willingness to stock EV models based on EV share of sales



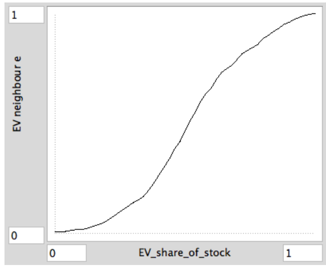
c. Consumer familiarity with EV based on EV share of on-road stock



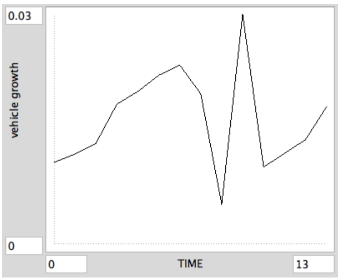
d. Weight of environmental concern in vehicle purchase choice



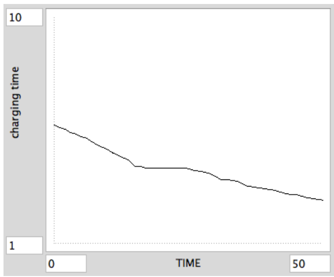
e. Phase-in curve for EV demand



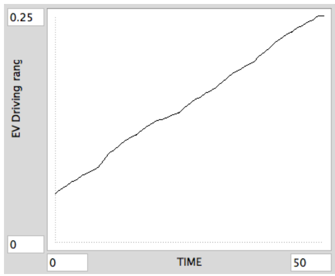
f. Neighbour effect based on share on on-road stock



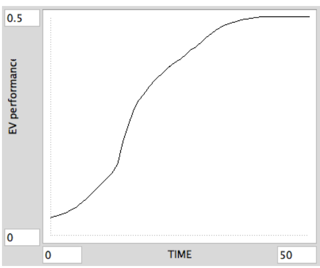
g. Historic vehicle stock growth rates



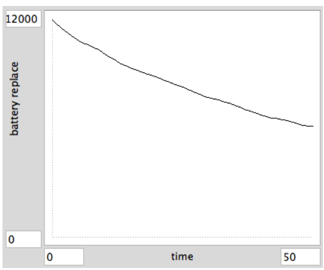
h. Battery charging time at 240v ('L2' charger)



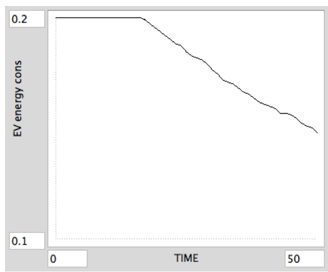
i. EV driving range on a full battery relative to CV



j. EV performance relative to CV



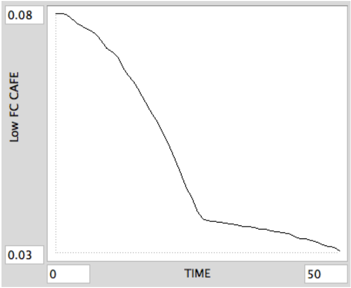
k. Battery replacement cost

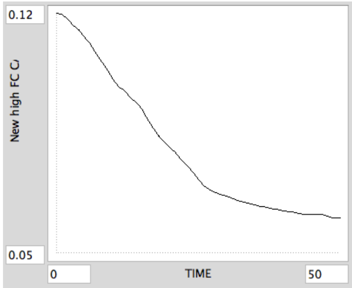


l. EV energy consumption per km driving

Figure B.2. Assumed feedback and time dependent curves in the vehicle market.

Conventional vehicle fuel efficiency module





a. Fuel efficiency (L/km) for new high-efficiency CV in each year

b. Fuel efficiency (L/km) for new low-efficiency CV in each year

Figure B.3. Manufacturers' fuel efficiency ratings for new vehicles in a model year, based on CAFE standards (EPA, 2010/2012).

Fuel market module

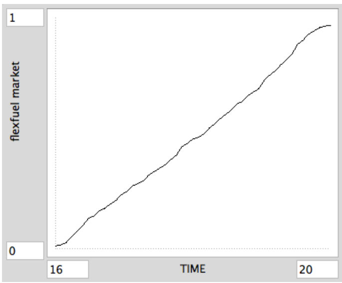
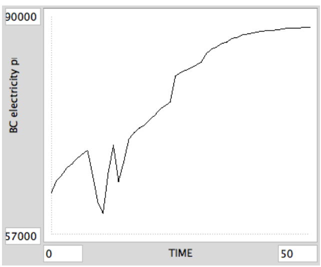
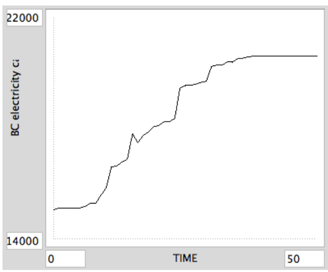
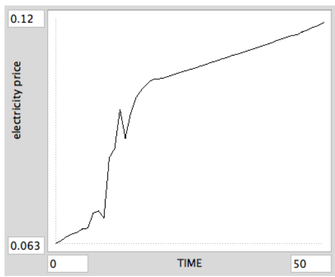


Figure B.4. New market share of flex-fuel (E85) vehicles. Optimistic based on Brazil's market success.

Energy supply curves







A. Total electricity generation by year (GWh)

B. Generation capacity (MW)

C. Residential electricity price (2010$/kWh)

Figure B.5. Electricity assumptions by year, from National Energy Board (NEB ,2016).