Designing a low carbon fuel standard to achieve deep GHG reduction targets: Insights from an energy-economy simulation model of British Columbia

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Abstract

Low carbon fuels are expected to play an important role in achieving long-term regional greenhouse gas (GHG) reduction targets within transport. The Low Carbon Fuel Standard (LCFS) is a policy instrument that has been used in British Columbia, California, Oregon, and Europe to reduce the GHG emissions associated with transportation fuels. I use a dynamic hybrid energy-economy model (CIMS-LCFS) coupled with a linear programming optimization model to explore the potential effectiveness of the LCFS at reducing GHG emissions in British Columbia under a variety of policy scenarios. This study also explores the potential for British Columbia's transportation sector, including passenger vehicles and freight vehicles, to achieve the province's mandated target of reducing GHG emissions by 80% below 2007 levels by 2050. CIMS-LCFS is a technologically-explicit, behaviorally-realistic energy-economy model that simulates the effects of climate policies on technology adoption and GHG emissions. The LP optimization model represents fuel supplier decisions to supply fuel to the market at the lowest possible cost subject to 50 unique constraints encompassing limited fuel availability, policy, and technical constraints. Results demonstrate that British Columbia's present suite of transportation policies are not strong enough to induce the emission reductions required to achieve the province's 2050 GHG target. These targets are only achievable for the entire transportation sector when the most stringent climate policies are combined, including a LCFS, a zero emission vehicle (ZEV) mandate, fuel efficiency standards and carbon pricing. My results indicate that the LCFS may have a particularly strong effect in decarbonizing the freight sector. In contrast, the LCFS may be less important for the passenger vehicle sector in the presence of other stringent transport policy (e.g. a ZEV mandate). Overall, I find that with careful policy design, the LCFS can be complementary to other stringent policies, and could play an important role in achieving 2050 GHG reduction targets in the transportation sector.

Keywords: low carbon fuel standard; LCFS; zero emission vehicle; carbon tax; low carbon fuels; climate policy; freight transport; personal transport

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List of Acronyms

AEO2015	*Annual Energy Outlook 2015*
B20	Mid-level biodiesel fuel blend (20% biodiesel, 80% diesel)
B.C.	British Columbia
BEV	Battery electric vehicle
CAD	Canadian dollars
CAFE	Corporate average fuel economy
CARB	California Air Resources Board
CNG	Compressed natural gas
DOE	United States Department of Energy
E85	Flex fuel (85% ethanol, 15% gasoline)
EER	Energy effectiveness ratio
EIA	United States Energy Information Administration
EPA	United States Environmental Protection Agency
FCEV	Hydrogen fuel cell vehicle
FFV	Flex fuel vehicle
gCO2e/MJ	grams of carbon dioxide equivalent per megajoule
GHG	Greenhouse gas
GJ	Gigajoule
HDRD	Hydrogenation-derived renewable diesel
kt CO2e	Kilotonnes carbon dioxide equivalent
LCFR	Low Carbon Fuel Requirement
LCFS	Low carbon fuel standard
LNG	Liquefied natural gas
LP	Linear programming
MJ	Megajoule
PHEV	Plug-in hybrid electric vehicle
PKT	Personal kilometers travelled
R100	High-level renewable diesel fuel blend (100% HDRD)
R20	Mid-level renewable diesel fuel blend (20% HDRD, 80% diesel)
RFR	Renewable Fuel Requirement
t CO2e	Tonnes carbon dioxide equivalent
TKT	Tonne kilometers travelled
USD	United States dollars
VKT	Vehicle kilometers travelled
WTW	Well-to-wheel
ZEV	Zero emission vehicle

Chapter 1. Introduction

In response to the growing concern of global climate change caused by anthropogenic greenhouse gas (GHG) emissions, several countries aim to achieve “deep” GHG emissions reductions, e.g. 80% below 2007 levels by 2050. Transportation is a petroleum-dominated sector that is responsible for a substantial portion of GHG emissions, approximately 23% of global energy-related carbon dioxide emissions (IPCC, 2014). Some argue that the transportation sector faces unique market conditions and large barriers to technological innovation of low carbon fuels and practices relative to other sectors (Andress et al., 2010; Yeh & Sperling, 2010), including the need for coordination among fuel producers and vehicle manufacturers (Sperling & Gordon, 2009), long time horizons needed for return on investments in fuel infrastructure (NRC, 2008), lack of fuel-on-fuel competition, and the market power of oil companies (Yeh & Sperling, 2010). Consequently, after several decades of “hype” and disappointment for different alternative fuels, petroleum still accounts for 95% of fuel use in Canada and the United States (Melton et al., 2016).

While many economists argue that carbon pricing is the most efficient way to reduce emissions in any sector (Tietenberg & Lewis, 2016), many regions are finding that it is politically difficult to enact a stringent carbon tax (Rhodes et al., 2014). There are additional transformative failures in transportation that need to be overcome beyond just market failures (Weber & Rohracher, 2012). Research suggests that governments can hinder technological transformation by continually shifting policy focus and funding from one vehicle technology to another (Melton et al., 2016). Further, governments can adversely impact innovation by publicly communicating unrealistic expectations regarding technology adoption (Melton et al., 2016). Therefore, some researchers believe that it is important for climate policies to have sustained public support and be adaptive to changes in technologies and markets (Greene & Ji, 2016; Melton et al., 2016).

In discussions of transportation climate policy, researchers often identify three distinct levers for reducing GHG emissions within the road transport sector: improve vehicle technologies, reduce GHGs associated with fuels, and reduce vehicle travel (Sperling & Yeh, 2009; Sperling & Eggert, 2014). While all three levers will likely be necessary to achieve significant GHG reductions, my research focuses on the potential to reduce emissions through the supply of low carbon alternative fuels. In particular, I focus on the low carbon fuel standard (LCFS), which requires fuel suppliers to progressively decrease the average GHG intensity of their fuels on a life cycle basis (Government of B.C., 2008). Of course, most climate policies are likely to affect all three levers to some degree; although the LCFS targets fuels, compliance will involve changes in vehicle drivetrains, and will likely affect travel demand via fuel and vehicle price changes.

1.1.Overview of low carbon fuel standards (LCFS)

To compare the benefits of different low carbon fuels, a LCFS focuses on the life cycle emissions of each fuel, which is commonly measured in terms of carbon intensity. A fuel's carbon intensity is the quantity of emissions per unit of energy associated with producing and consuming the fuel, measured in grams of carbon dioxide equivalent per megajoule (gCO_2e/MJ) (Government of B.C., 2008). A fuel's life cycle accounts for all of the emissions associated with growing, producing, transporting, and consuming a transportation fuel. On a life cycle basis, for example, substituting a unit of energy from petroleum gasoline with a unit of energy from conventional Canadian wheat-based ethanol can reduce carbon intensity by approximately 40% to 78% (B.C. MEM, 2016a). The wide-range of possible emission reductions from wheat ethanol can be attributed to the different production processes and equipment used to harvest the wheat feedstock, to produce the ethanol fuel, and to transport the finished fuel to refineries and retail locations. Additional emission reductions can be achieved if the ethanol is produced from lower carbon feedstocks, such as cellulose (e.g. organic compound found in wood, algae, and other plants). Also, different life cycle models will often calculate different carbon intensity values or ranges for the same fuel, due to differing assumptions about these processes or boundaries of analysis.

There are many alternative fuels that have the potential to reduce emissions when used in replacement of petroleum gasoline or diesel. Biodiesel is a renewable fuel that is composed of fatty acid methyl esters and produced from vegetable oil or animal fat via transesterification, a process that involves reacting the oil or fat in the presence of a catalyst with an alcohol (Knothe et al., 2015). Hydrogenation-derived renewable diesel (HDRD) is commonly produced via hydroprocessing and is nearly chemically identical to conventional diesel (Miller, 2012; NRC, 2012). Although they differ in chemical composition, both biodiesel and HDRD can be produced from vegetable oils and animals fats. Using typical production methods, on a life cycle basis, replacing a unit of energy from petroleum diesel with a unit of energy from biodiesel or HDRD can reduce emissions by approximately 40% to 95% (B.C. MEM, 2016a). However, in some cases, alternative fuels can be more GHG-intensive than petroleum gasoline or diesel on a life cycle basis. For example, biodiesel produced from palm fatty acid distillate can actually increase emissions by approximately 7% relative to petroleum diesel (B.C. MEM, 2016a). The importance of measuring a transportation fuel's GHG emissions on a life cycle basis is further evidenced when looking at liquefied natural gas (LNG). Compared to petroleum diesel, fossil-based LNG can reduce emissions by approximately 33% or it can increase emissions by more than 20%. The large difference in emission reduction potential can be attributed to the different methods used to cool and condense the natural gas into a liquid. Further reductions can be realized if renewable sources of LNG are used, such as biogas produced from landfills. Moreover, emission reductions from using electricity and hydrogen in replacement of petroleum gasoline or diesel can also vary widely depending on fuel production processes.

However, in almost all cases these fuels result in net emission reductions due to the relatively higher efficiency of electric and hydrogen vehicles.

Versions of a LCFS have been used in British Columbia, California, Oregon and Europe to reduce the GHG emissions associated with transportation fuels – with the goal of inducing uptake of alternative, low-carbon fuels like those noted above. Furthermore, the Government of Canada recently announced its intentions to develop a national clean fuel standard, potentially modelled after British Columbia's LCFS (Government of Canada, 2016). Most versions of the LCFS require fuel suppliers to reduce the average life cycle carbon intensity of their transportation fuel mix (Government of B.C., 2008). To comply with the LCFS, fuel suppliers can lower their average carbon intensity by blending an increasing amount of renewable fuel into petroleum gasoline and diesel or by supplying lower carbon alternative fuels, such as hydrogen or electricity. Research suggests that the LCFS and other supply-focused policies are strongly supported by the public; Rhodes et al. (2014) surveyed 475 British Columbians and found that respondent support for the LCFS was about 90%, compared to just 56% support for British Columbia's carbon tax.

The LCFS is a hybrid of command-and-control regulation (what I will call "regulation") and market-based emissions trading. It is regulation-based in the sense that there is a carbon intensity target (or limit) that fuel providers must comply with, and it is market-based in that fuel suppliers can trade and bank emission credits, thus promoting cost-effectiveness (Ferrell & Sperling, 2007b). According to economic theory, adding market-based features to a regulation can make it more economically efficient (Tietenberg & Lewis, 2016). Although the LCFS prescribes a limit for the average carbon intensity of a fuel supplier's fuel mix in a given year, it allows firms the freedom to choose from any available fuels to meet the target (Sperling & Yeh, 2009; Andress et al, 2010). A fuel supplier generates credits under the LCFS by supplying a fuel with a carbon intensity below the limit (e.g. most of the low carbon fuels noted above), and they incur debits by supplying a fuel with a carbon intensity above the limit (e.g. petroleum gasoline and diesel) (Ferrell & Sperling, 2007b). To remain compliant, a fuel supplier must ensure that debits incurred from supplying higher carbon fuels are offset by credits generated from supplying lower carbon alternatives. A fuel supplier can also bank surplus credits if they over-comply with the carbon intensity limit in a given year. If a fuel supplier is out of compliance, the credit deficit can be offset by either using credits banked from previous years, or by purchasing credits on the open market (Yeh et al., 2013).

Critiques of the LCFS tend to focus on three different aspects: economic efficiency, effectiveness, and uncertainty. First, some economists suggest that the LCFS acts as a tax on any fuel with a carbon intensity above the standard, but acts as a subsidy for any fuel with a carbon intensity below the standard (Holland et al., 2009). In terms of economic efficiency, a LCFS is argued to be somewhat inefficient because it requires any fuel emitting carbon to be taxed the amount of its negative externality (not subsidized) in equilibrium (Holland et al., 2009). Instead, some researchers advocate for an economy-wide carbon tax, which would allow the market to efficiently achieve the least cost reductions across all sectors (Creutzig et al., 2011). However, proponents of the LCFS believe that technology-specific policy is needed to overcome the large technological barriers to innovation within the relatively inelastic transportation sector (Hughes et al., 2006; Farrell & Sperling, 2007b; Yeh & Sperling, 2010).

A second critique is the concern over the effectiveness of the policy at reducing global GHG emissions. In particular, some researchers believe that the policy may result in fuel shuffling and leakage (Yeh & Sperling, 2010; Creutzig et al., 2011). In other words, fuel suppliers may seek to comply by shifting lower carbon fuels to jurisdictions with a LCFS and supplying higher carbon fuels to those jurisdictions without a LCFS. Shuffling, or leakage, is a common problem when regulations differ across geographical regions (Yeh & Sperling, 2010). If significant leakage were to occur, the global benefits of the LCFS could be insignificant (Reilly et al., 2007). As with most climate policy, the issue of leakage can be mitigated by having additional jurisdictions adopt a LCFS-type policy (Farrell & Sperling, 2007b).

A final concern with the LCFS focuses on uncertainty in estimating the full life cycle emissions associated with a given fuel—in particular regarding emissions from land use change and biofuel production. There are two types of land use changes: direct and indirect. Direct land use change relates to changes in the land where the biofuel feedstock is physically grown (Malins et al., 2014). In contrast, indirect land use change occurs when the production of biofuels on agricultural land displaces agricultural production and induces additional land to be cleared, ultimately causing an increase in net GHG emissions (Yeh & Sperling, 2010; Ben Aoun & Gabrielle, 2017). Any policy that incentivizes or requires the production and supply of biofuels faces the challenge of representing (or neglecting) the complexity of indirect land use change. Mathematical models have been developed to estimate the magnitude of indirect land use change, but there is still major uncertainty in understanding its true value (Crutzen et al., 2007; Searchinger et al., 2008; Kim et al., 2009; Melillo et al., 2009; Creutzig et al., 2011). Presently, California’s LCFS accounts for indirect land use change while British Columbia’s LCFS does not.

1.2. California’s LCFS

California has pioneered the LCFS as part of enacted legislation requiring the state to reduce its GHG emissions by 80% below 1990 levels by 2050. California’s transport sector is the largest emitter of GHG emissions in the state, responsible for 37% of emissions in 2014 (CARB, 2016a). To achieve its climate goals, the California Air Resources Board (CARB) believes that the transportation sector will need to transform from its current petroleum-dominated state to one that includes zero emission vehicle (ZEV) technologies, low carbon fuels, and greater fuel efficiency (CARB, 2012). To facilitate this transformation, California has enacted a suite of regulations (Sperling & Eggert, 2014). Specifically, California has implemented a zero emission vehicle (ZEV) mandate, vehicle purchase rebates, refuelling infrastructure investments, HOV lane access, information programs, fuel economy standards, alternative fuel production incentives, a cap-and-trade system, and a LCFS (California Governor's Office, 2013; CCES, 2014). A ZEV mandate is compulsory policy that requires auto manufacturers to sell an increasingly specified percentage of ZEV vehicles per year (Collantes & Sperling, 2008). Policies that regulate vehicle composition, such as a ZEV mandate, are thought to play a complementary role in achieving LCFS targets. Increasing alternative fuel demand through an increase in ZEVs provides an opportunity to supply additional low carbon fuels to generate LCFS compliance credits. Note that while this potential for complementarity would provide benefits in terms of overall effectiveness, it also complicates efforts to attribute GHG emissions reductions to one policy or the other.

In 2007, California implemented a LCFS as part of this suite of climate policies, requiring fuel suppliers to reduce the carbon intensity of transportation fuels sold in the state by 10% by 2020 (Ferrell & Sperling, 2007a). California designed the standard to have increasing stringency in later years – the intention being to ease fuel suppliers into the LCFS while allowing time for innovation. The LCFS program has been successful in reducing GHG emissions and increasing the use of alternative fuels. In 2015, alternative fuels comprised 8.1% of California's transportation fuels by energy content, up from 6.2% in 2011 (Yeh & Witcover, 2016). Furthermore, the average carbon intensity of the alternative fuels supplied decreased 21% over that same time period (2011 to 2015), from 86 down to 68 gCO_2e/MJ (Yeh & Witcover, 2016). As a result, total emission reductions from 2011 to 2015 were 16.8 million tonnes CO_2e (Yeh & Witcover, 2016) – though as noted above, it is difficult to determine how much of these reductions are due to the LCFS versus other climate policies. California's LCFS only required a reduction of 9.2 million tonnes CO_2e during that period; therefore, fuel suppliers in California have over-complied with the LCFS by 81% (Yeh & Witcover, 2016). The surplus credits from over-compliance in 2011 to 2015 could play an important role in ensuring compliance with increasingly stringent targets in future years (ICF International, 2013).

1.3. British Columbia's LCFS

Similar to California, the Government of the Canadian Province of British Columbia aims to reduce GHG emissions by 80% below 2007 levels by 2050 (Government of B.C., 2007). Transportation is responsible for 38% of GHGs in British Columbia, more than any other economic sector (B.C. CAS, 2016). Moreover, British Columbia's GHG emissions from transport have increased 32% from 1990 to 2014 (B.C. CAS, 2016). In 2008, British Columbia implemented its own LCFS, largely based on California's policy. Similar to California, British Columbia aims to reduce transportation fuel carbon intensity by 10% by 2020, and has recently committed to extending the LCFS by requiring a 15% reduction in carbon intensity by 2030 (Government of B.C., 2016b).

There are two key differences between California's and British Columbia's LCFS. First, British Columbia's smaller, resource-based economy has access to different low carbon transportation fuels at different costs then California. For example, British Columbia's electricity has the potential to significantly reduce transportation emissions because 98% of the electricity produced in the province is from clean or renewable sources (Government of B.C., 2016b). In comparison, the carbon intensity of California's average electricity mix is over five times that of British Columbia (CARB, n.d.; Government of B.C., 2016a). Having an abundance of low cost, low carbon electricity also provides British Columbia the opportunity to produce other fuels at a low carbon intensity, such as hydrogen from electrolysis. Second, California has incorporated indirect land use change into their assessment of the carbon intensity of crop-based biofuels (CARB, n.d.). The addition of indirect land use change adds between 12 to 71 gCO_2e/MJ to the carbon intensity calculation (CARB, n.d.; CARB, 2016b). In contrast, British Columbia's LCFS only accounts for emissions from direct land use changes due to lack of certainty surrounding the magnitude of indirect land use change.

British Columbia's LCFS appears to have been successful in reducing GHG emissions and increasing the use of alternative fuels – though again it is difficult to isolate the effects of this one policy. In 2015, alternative fuels comprised 6% of the transportation fuels by energy content, up from 3.5% in 2010 (B.C. MEM, 2016b). Furthermore, the average carbon intensity of the alternative fuels supplied decreased over the same period. From 2010 to 2015, the average carbon intensity of ethanol supplied decreased 11% from 56 to 49 gCO_2e/MJ; the average biodiesel carbon intensity decreased 55% from 35 to 16 gCO_2e/MJ; and the average HDRD carbon intensity decreased 65% from 48 to 17 gCO_2e/MJ (B.C. MEM, 2016b). As a result, total emission reductions from 2010 to 2015 were 5.1 million tonnes CO_2e (B.C. MEM, 2016b). In 2015, the LCFS required a 2.5% reduction in carbon intensity from the baseline fuel mix; fuel suppliers over-complied by achieving a 3.4% reduction in carbon intensity (B.C. MEM, 2016b). Moving forward, compliance with the 2020 target appears to be feasible and the provincial government has committed to setting a 2030 target of 15% reduction in carbon intensity below 2010 values (Government of B.C., 2016b).

1.4.Other studies that have modelled the LCFS

As noted above, it is difficult to attribute any observed emissions reductions to the LCFS or any other climate policy. To explore the effects of such policies, particularly in the long-term, several studies have used modeling exercises to estimate or simulate the effectiveness, feasibility and efficiency of a LCFS. Some of these studies have used a spreadsheet accounting tool to assess the feasibility of achieving LCFS reduction targets in California and other jurisdictions, where assumptions are made regarding vehicle sales, fuel efficiency, and fuel intensities (Farrell & Sperling, 2007a; ICF International, 2013; Malins et al., 2015). Other modelling research focuses on the cost-effectiveness of the LCFS at reducing emissions, using either a simplified economic model or a proprietary simulation model (Holland et al., 2009; BCG, 2012). Finally, some studies have used technologically-explicit, behaviorally-realistic energy-economy models to simulate the LCFS and other policies, with the goal being to assess the least cost options available to California to achieve deep emission reductions across the entire economy (McCollum, 2011; McCollum et al., 2012; Yang et al, 2015; Yang et al., 2016).

In terms of the feasibility of LCFS targets, several studies indicate that there will be sufficient quantities of low carbon fuels to achieve a 10% carbon intensity reduction by 2020 (Farrell & Sperling, 2007a; ICF International, 2013; Malins et al., 2015), which aligns with targets set in California and British Columbia. Two studies used the VISION spreadsheet model to assess the potential for either California or the Pacific region – British Columbia, California, Oregon, and Washington – to achieve a 10% reduction in carbon intensity (Farrell & Sperling, 2007a; Malins et al., 2015). The VISION model was originally developed by the Argonne National Laboratory to provide estimates of the potential energy use and carbon emission impacts of advanced vehicle technologies and alternative fuels through the year 2100 (Argonne National Laboratory, n.d.). The VISION model is essentially a causal tree, where exogenous inputs of vehicle sales, fuel efficiencies, fuel shares, and fuel intensities lead to an output of GHG emissions (Fiddaman, 2008). Both studies used scenario analyses that exogenously varied vehicle adoption rates, technological advancement, policy adoption, industry investment, and availability of emerging low carbon fuels. From the results of the scenario analyses, the authors estimated that carbon intensity reductions of between 5 to 15% are possible by 2020, and reductions of 14 to 21% are possible by 2030 (Farrell & Sperling, 2007a; Malins et al., 2015). A third study, completed by the consulting firm ICF International, used a proprietary optimization model coupled with the REMI (Regional Economic Models, Inc.) macroeconomic model to illustrate California's ability to achieve its 2020 reduction target with only modest changes to the diversity of fuels (ICF International, 2013).

A study focusing on LCFS cost-effectiveness found that the policy would likely result in a reduction of GHG emissions, albeit at a very high cost relative to other climate policies (Holland et al., 2009). Specifically, Holland et al. (2009) used a simplified economic model to illustrate that a national U.S. LCFS modeled after California's LCFS could reduce GHG emissions, but with an average cost of between $300 to $2300 USD per tonne of CO_2. The authors' model represented one firm maximizing profit by supplying two fuels: a high carbon gasoline and a low carbon ethanol (Holland et al., 2009). Instead of implementing California's LCFS on a national level, the authors propose a "historical-baseline LCFS" that would set a unique baseline for each firm (of which reductions are measured against) based on each firm's historic energy production (Holland et al., 2009). The study estimated that the "historical-baseline LCFS" could achieve the same emission reductions as California's LCFS, but at a lower range of average costs – between \$60 to \$900 USD per tonne of CO_2 (Holland et al., 2009). Because the analysis only looked at the LCFS in isolation, there was no consideration to how complementary policies could achieve greater emission reductions while spreading out the costs of abatement across two or more policies. Further, the use of the simplified economic model containing only two fuels without any endogenous feedbacks limits the real-world applicability of the study's results and conclusions.

An additional study assessing the cost-effectiveness of the LCFS, completed by the Boston Consulting Group (BCG) on behalf of the Western States Petroleum Association, used a proprietary model to analyze the impact of California's Global Warming Solutions Act (AB 32) on emissions, refining economics, employment, and government revenues (BCG, 2012). BCG found that the LCFS is infeasible, has an extremely high cost of compliance, and will result in the shutdown of several California refineries (BCG, 2012). The results of BCG's proprietary modeling exercise are difficult to interpret, because the model used in the analysis was not made available for peer-review and evaluation. However, the Institute of Transportation Studies at UC Davis gathered eight expert reviewers to analyze BCG's study and results, critiquing many input assumptions, including what seem to be overly conservative assumptions of very few alternative fuel vehicles on the road by 2020 and limited amounts of low carbon fuels available by 2020 (UC Davis, 2013a). In contrast to BCG's predictions, British Columbia data indicates that an increasing amount of low carbon fuels are becoming available each year (B.C. MEM, 2016b).

There are several studies that take a more comprehensive, longer-term view of the LCFS, finding that policies that support both low carbon fuels and alternative fuel vehicles will likely play an important role in achieving an 80% reduction in GHGs by 2050 (McCollum, 2011; McCollum et al., 2012; Yang et al, 2015; Yang et al., 2016). Two of these studies used the CA-TIMES optimization model to explore the potential evolution of California's energy system, analyzing the least-cost technology options for achieving California's 80% GHG reduction by 2050 (McCollum, 2011; McCollum et al., 2012, Yang et al, 2015; Yang et al., 2016). CA-TIMES is a bottom-up, technologically-rich optimization model that uses California specific data and is based upon the MARKAL-TIMES equilibrium-modeling framework (UC Davis, 2013b). The objective of the model is to determine the specified energy services or demands at the lowest cost (minimum total net present value) subject to technical, social, and policy constraints. The McCollum et al. (2012) study did not directly model the LCFS, but did conclude that the policy was expected to be met under the GHG reduction scenario. In this scenario, the 2050 GHG target was achieved with low carbon biofuels, hydrogen, and electricity playing an important role in reducing GHG emissions, accounting for 26%, 8%, and 2% of fuel consumption by 2050 respectively (McCollum et al., 2012). The Yang et al. (2016) study builds off of the CA-TIMES modeling exercise completed by McCollum et al. (2012) by improving aspects of the model, including incorporating heterogeneity and consumer choice, technology learning-by-doing, and demand response. Yang et al. (2016) take a similar approach to my study by modelling the LCFS as a policy constraint within the transportation sector. The authors analyzed several scenarios and found that zero emission vehicles (ZEVs) played an important role in the passenger vehicle sector, accounting for 79% of the miles travelled by 2050 (Yang et al., 2016). Furthermore, low carbon biofuels captured a relatively large share of the fuel market (31 to 39%) along with hydrogen and electricity; gasoline and diesel consumption decreased dramatically by 2050 (82% below 2010 levels) (Yang et al., 2016). In other words, low carbon fuels in several studies played an important role in least-cost compliance with deep GHG reduction targets (McCollum, 2011; McCollum et al., 2012; Fulton & Miller, 2015; Robins et al., 2015; Yang et al, 2015; Yang et al., 2016).

These previous studies have largely focused on California's LCFS by examining the policy's potential feasibility, economic efficiency, and ability to reduce GHG emissions – with little focus on other regions. Moreover, efforts to model the LCFS have mainly looked at short-term reduction targets using simplified, static accounting tools. Although useful, static accounting tools are largely dependent on their exogenous input assumptions regarding vehicle adoption rates, fuel use, and technological advancement. While a few studies did take longer-term, dynamic approaches to modelling transportation climate policy, they did not look specifically at the potential effectiveness of the LCFS; rather they modelled potential emission reductions from a full suite of climate policies across all sectors of the economy. Although the CA-TIMES model does incorporate some behavioural realism in transport (e.g. segmenting the market and including non-monetary factors based on differing consumer preferences), the model does not appear to allow for changes to travel demand as a result of changes to the cost of vehicles and driving. This feedback is important when modelling stringent climate policy that can significantly raise the cost of owning and operating a vehicle. More importantly for the sake of policy-relevance, the CA-TIMES modelling exercises conducted by McCollum et al. (2012) and Yang et al. (2016) modelled the 2050 GHG target as a constraint, thus forcing the reduction target to be met in every "successful" scenario simulation. It then becomes difficult to determine if the resulting vehicle market shares and fuel consumption occurred as a result of policy (e.g. from the LCFS or the zero emission vehicle mandate) or as a result of the model fulfilling the 2050 GHG target. Next, I explain my novel approach to simulating the effects of a LCFS and other climate policies in the transportation sector.

1.5.Research approach and objectives

To improve insights into the long-term effects of a LCFS, including various dynamics in transport, I simulate the transportation sector out to 2050 using a hybrid energy-economy model that is well-suited for evaluating policy effects on technology uptake and usage in a manner that is both technologically-explicit and behaviourally-realistic. This study offers several unique contributions to LCFS literature. The model incorporates a number of endogenous factors including vehicle technology adoption, declining capital costs and intangible costs, personal travel mode choice, fuel switching for multi-fuel capable vehicles, travel demand feedbacks, declining fuel production costs and prices, and alternative fuel availability at refuelling locations. My research is also the first LCFS-focused study to incorporate endogenous fuel supply decisions based on the financial costs of different feedstocks and fuels. Further, this study is the first to model the LCFS in the unique context of the Canadian Province of British Columbia. It is also the first study to analyze the potential effectiveness of the LCFS within two distinct subsectors of transportation: personal travel and freight transport. Finally, I examine the potential complementarity of the LCFS with other transportation policies – a zero emission vehicle (ZEV) mandate (like that in California and Quebec), vehicle GHG standards (e.g. U.S. CAFE standards), and a carbon tax – in an effort to understand the optimal policy environment for a successful LCFS.

Specifically, I use a vehicle choice model of the British Columbia transportation sector coupled with a fuel supply optimization model to explore the effects that the LCFS and other policies have on vehicle composition, fuel supply, and GHG emissions. The vehicle choice model (which I call "CIMS-LCFS") is adapted from the energy-economy model CIMS, which has been used to evaluate climate policies within a number of sectors (Jaccard et al., 2003; Mundaca et al., 2010; Murphy & Jaccard, 2011) with some research focusing on the transportation sector (Fox, 2013; Sykes, 2016; Fox et al., 2017). CIMS-LCFS simulates the composition of both the personal and freight transportation sectors in British Columbia out to 2050. Consumers make vehicle purchase decisions based on perceptions of both monetary and non-monetary attributes. In turn, the linear programming optimization model simulates fuel supply decisions for meeting consumer demand for fuel from CIMS-LCFS, under different policy scenarios.

I run a series of policy package scenarios to explore the effectiveness of British Columbia's LCFS at reducing GHG emissions when accompanied with other transportation policies – specifically to identify which affects are "additive" or incremental to the effects of other policies, and which are redundant. To isolate the GHG effectiveness (or impact) of the LCFS, I run each policy scenario with and without the LCFS. I then analyze the difference in emission reductions that occur as a result of the inclusion of the LCFS. I consider the LCFS complementary if it has a positive incremental effect on GHG emission reductions in every period of the simulation when included in a policy package scenario. Meaning, the inclusion of a LCFS always results in additional emission reductions that would not have occurred without the LCFS. Further, I consider the LCFS transitional if it has a declining positive incremental effect on GHG emission reductions during the early periods of a simulation before the incremental effect ultimately declines to zero. The term transitional is used because it is describing a LCFS that is effective at reducing emissions as conventional gasoline and diesel vehicles are replaced by alternative vehicle technologies utilizing lower carbon fuels. However, once the majority of the conventional gasoline and diesel vehicles are replaced, the LCFS is no longer effective at reducing emissions. Finally, I consider the LCFS redundant if it does not have a positive incremental effect on GHG emission reductions at any point during a simulation (i.e. from 2015 to 2050). In other words, the LCFS is redundant if its inclusion in a policy scenario never results in additional emission reductions above the reductions that occur in that policy scenario without the LCFS. I then explore the potential for British Columbia's transportation sector to meet its provincial GHG target in 2050. I accomplish this objective by simulating policy of various stringencies and analyzing the resulting GHG emission reductions that occur across the entire British Columbia transportation sector.

In summary, my research objectives are:

1. To assess the potential incremental effectiveness of the LCFS at reducing GHG emissions when accompanied with other types of transport policy (complementary, transitional or redundant); and
2. To simulate the overall effects of British Columbia implementing a suite of transportation policies, specifically in achieving its 2050 GHG targets (LCFS with a ZEV mandate, carbon tax, and vehicle GHG standards).

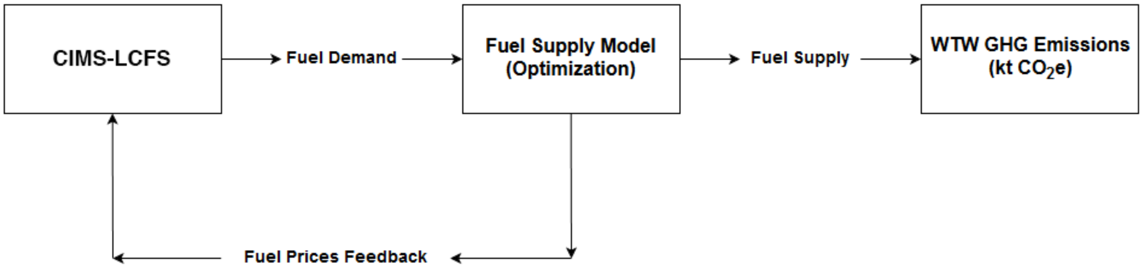
Chapter 2. Methods

To accomplish my research objectives, I simulate policy scenarios using two interconnected models: an Excel-based vehicle choice model ("CIMS-LCFS") and a fuel supply optimization model (Figure 1). In this chapter I provide a detailed description of the underlying framework for both the CIMS-LCFS model and the fuel supply optimization model, including exogenous inputs, assumptions, and key endogenous functions. I then discuss my methodology for calculating GHG emissions before presenting the different policy scenarios. However, first I give a short overview of the two models and my approach to uncertainty.

CIMS-LCFS simulates vehicle composition in British Columbia in five year periods beginning in 2015 and ending in 2050. In each five year period, a portion of the existing vehicle stock is retired according to exogenous retirement schedules derived from literature, and demand for new vehicle technologies is assessed based on the current vehicle stock and an exogenous growth factor. Total vehicle demand for the personal transportation sector (described in section 2.1.) is measured in personal kilometers travelled (PKT) and vehicle kilometers travelled (VKT) while total vehicle demand for the freight transportation sector (described in section 2.1.) is measured in tonne kilometers travelled (TKT). To satisfy the demand for new vehicles, the model simulates how heterogeneous consumers purchase different vehicle technologies based on relative costs – capital costs, energy costs, maintenance costs, and intangible costs. CIMS-LCFS is calibrated to the *Reference Case* of the U.S. Energy Information Administration's (EIA) *Annual Energy Outlook 2015* (*AEO2015*) (U.S. EIA, 2015b). Calibration was achieved through adjusting vehicle technology capital costs and intangible costs in order to align tailpipe GHG emissions, vehicle technology market shares, and total vehicle demand with the *AEO2015 Reference Case* out to 2040.

The fuel supply model is a linear programming (LP) optimization model that is designed to be a representation of petroleum fuel suppliers at the aggregate level. LP optimization models have been used frequently for a variety of petroleum refinery operational analyses and planning (Symonds, G. H., 1995; Pinto et al., 2000; Hirshfeld et al., 2014; Kwasniewski et al., 2016). As illustrated in Figure 1 below, after CIMS-LCFS has determined vehicle composition in a given period, the resulting fuel demand becomes an input for the fuel supply model; fossil-based petroleum fuel suppliers (hereby called 'fuel suppliers') supply petroleum gasoline and diesel to fulfill the demand from the British Columbia transportation sector. In addition, fuel suppliers can supply alternative fuels – such as ethanol, biodiesel, and electricity – to comply with regulation in the policy scenarios. The optimization model's objective function is set to minimize the cost of supplying fuel to British Columbia subject to a number of predefined constraints, including the carbon intensity limit required by a given LCFS scenario (described in section 2.7.). Well-to-wheel (WTW) GHG emissions are then calculated based on the fuel supplied within the LP optimization model.

Figure 1. Excel-based interconnected simulation model structure (per period)



I use single-value deterministic sensitivity analysis to explore how variations in seven key parameters affect the results of my two objectives: the potential effectiveness of the LCFS at reducing GHG emissions when accompanied with other transport policy and the well-to-wheel (WTW) GHG emission reductions realized from implementing a suite of transportation policies to achieve British Columbia's 2050 GHG target. Any attempts to model long-term technological change involves a high degree of uncertainty in future technology characteristic and costs (Rosenberg, 1998; Kann & Weyant, 2000; Yang et al., 2016). Some emerging vehicle technologies and fuels may ultimately fail to penetrate the market, while others may experience widespread adoption. Modelling results can depend largely on underlying assumptions about endogenous and exogenous processes, and the methods used for simplifying a model's structure in representing real world systems (Kann & Weyant, 2000). For linear programming optimization models, input assumptions regarding technology costs are critical parameters in determining which technologies meet energy demands (Yang et al., 2016). For this study, I quantify uncertainty by using single-value deterministic sensitivity analysis. This approach involves setting particular parameters of interest, e.g. those that are expected to have high uncertainty levels, to relatively extreme points while holding all other variables at nominal values (Kann & Weyant, 2000). In circumstances where parameters are closely related, I vary multiple parameters jointly as this can produce a more practical measure of sensitivity (Kann & Weyant, 2000).

Table 1 (below) provides an overview of the exogenous inputs, key endogenous functions, and outputs of both CIMS-LCFS and the fuel supply optimization model. I then describe each input, function, and output in greater detail in the subsequent sections.

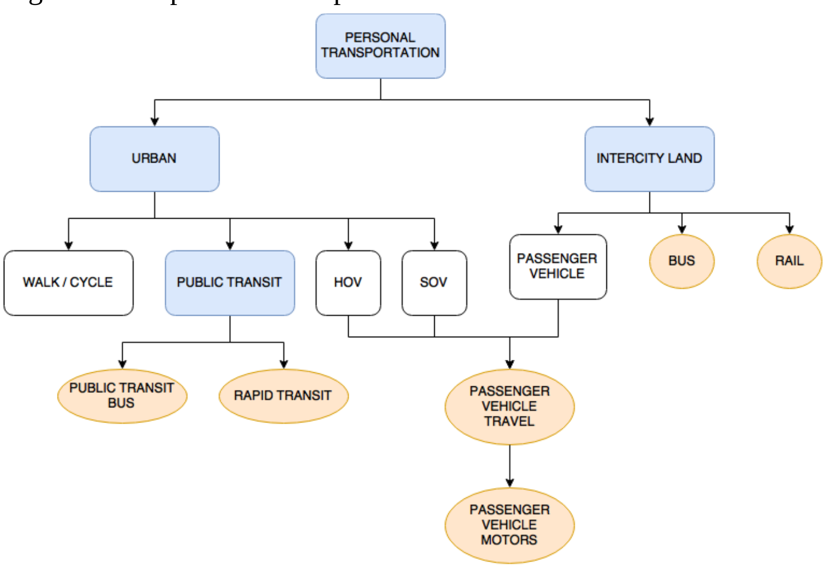
Table 1. Overview of the interconnected simulation model

CIMS-LCFS		
Exogenous Inputs	**Key endogenous functions**	**Outputs**
Personal and vehicle kilometers travelled (PKT/VKT) demand BAU growth rate	Vehicle market share competition	Vehicle technology market shares and total stock
Tonne kilometers travelled (TKT) demand BAU growth rate	Declining capital cost function	Quantity of fuel demanded by the British Columbia transportation sector
Vehicle financial and intangible costs	Declining intangible cost function	
Vehicle fuel efficiency attributes	Declining fuel production costs (end-use fuel prices)	
Vehicle retirement rates	Service cost function (vehicle mode choice)	
Initial energy / fuel prices	Fuel choice market share competition	
Freight transport mode choice between marine, land, and air; within land freight the choice between trucks or rail	Travel demand feedback for personal vehicles, light/medium freight trucks, and heavy freight trucks (policy scenarios only)	
Declining capital cost parameters	Fuel choice in flex fuel vehicles (E85 vs. Gasoline)	
Declining intangible cost parameters	Fuel choice in conventional diesel vehicles (B20/R20 vs. R100 vs. Diesel)	
Purchase behavior parameters		
Vehicle and travel demand elasticities		
Fuel Supply Optimization Model		
Exogenous Inputs	**Key endogenous functions**	**Outputs**
Initial fuel production cost parameters	Declining fuel production costs	Well-to-wheel GHG emissions
Carbon intensities for transportation fuels		Quantity and type of fuel supplied under the LCFS (policy scenarios only)
"Blend wall" advancement (E10 to E15, B5/R5 to B10/R10)		
Quantity of emerging alternative fuels available to the British Columbia marketplace		

2.1. Personal and freight transportation sectors

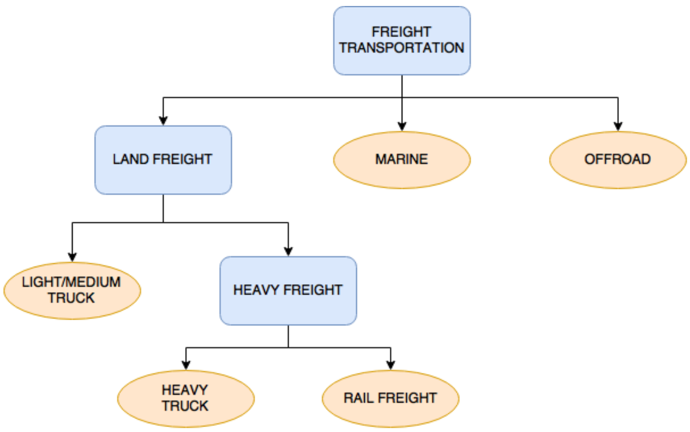
CIMS-LCFS is comprised of two distinct sectors: the personal transportation sector and the freight transportation sector. As depicted in Figure 2 below, the personal transportation sector incorporates two types of travel in British Columbia: urban travel within cities and travel between cities (intercity). The initial travel demand – measured in PKT – is taken from the full CIMS model with the subsequent growth in demand being based on an exogenous PKT forecast from *AEO2015* (U.S. EIA, 2015b), and is split between urban and intercity based on data from the full CIMS model. Within the urban subsector, the different modes of transport – walk/cycle, public transit, single occupancy vehicle (SOV), and high occupancy vehicle (HOV) – compete against one another based on their respective service costs (described in section 2.4.). Similarly, the three modes of intercity transport – passenger vehicle, bus, and rail – also compete against one another based on their respective service costs. Subsequently, personal kilometers travelled (PKT) is converted to vehicle kilometers travelled (VKT) based on exogenous service requirement parameters, taken from the full CIMS model. The service requirement parameters assume a fixed number of passengers (measured by PKT) for each travel mode (measured in VKT). For example, intercity passenger vehicles are assumed to have an average of two passengers (service requirement parameter of 66%), HOV travel within cities is assumed to be three passengers (service requirement parameter of 33%), and the remaining subsectors assume a single passenger (e.g. a 1:1 PKT to VKT ratio). Moreover, in the passenger vehicle sector, VKT for personal vehicles are then designated as either cars or trucks of various sizes, determined by the market share competition algorithm (described in section 2.2.). The CIMS-LCFS model adjusts the VKT for passenger vehicles based on the different sizes of vehicles (e.g. large truck, small truck, large car, or small car), with larger vehicles using slightly more VKT than their smaller counterparts. Referring to Figure 2, the circular subsectors contain vehicle technologies that compete against one another to satisfy VKT demand (described in section 2.2.).

Figure 2. The personal transportation sector in the vehicle choice model.



The freight transportation sector consists of five distinct subsectors: offroad, marine, rail, light/medium trucks, and heavy trucks (Figure 3). The offroad subsector is comprised of all non-road vehicles such as forklifts, ATVs, and mining trucks while the marine subsector consists of commercial watercraft used for moving goods (i.e. tankers and barges). The light/medium truck subsector consists of short haul freight vehicles while the heavy truck sector represents long haul class eight freight trucks. I took the initial total freight vehicle demand from the full CIMS model while basing growth in that demand on an exogenous TKT forecast from *AEO2015* (U.S. EIA, 2015b). As illustrated in Figure 3, the initial TKT forecast is exogenously split between land freight, marine and offroad in each period. Subsequently, land freight is exogenously split between light/medium truck and heavy freight, which is further split between heavy truck and rail. The exogenous splits used in the model are based on historical energy demand and remain static throughout the modeling exercise (NRC, 2013). The circular subsectors in Figure 3 contain vehicle technologies that compete against one another to satisfy TKT demand (described in section 2.2.).

Figure 3. The freight transportation sector in the vehicle choice model.



2.2. Vehicle technology market share competition

To meet projected VKT or TKT demand, eleven distinct vehicle technologies compete for market share: diesel, gasoline, compressed natural gas (CNG), liquefied natural gas (LNG), hybrid electric (HEV), plug-in hybrid electric (PHEV), battery electric (BEV), fuel cell electric (FCEV), propane, flex fuel (FFV), and heavy fuel oil. As depicted in Table 2, not all vehicle technologies are available for both passenger and freight vehicles. In addition, some vehicle technologies are capable of using more than one type of fuel. Specifically, conventional diesel engines are capable of using diesel, a blend of diesel and biodiesel or HDRD (B20/R20), or 100% HDRD (R100). Similarly, flex fuel vehicles (FFVs) are capable of using either gasoline or a blend of gasoline and ethanol (E85). Multi-fuel capable vehicles are described in greater detail in Section 2.6.

First, to fulfill projected travel demand, the existing vehicle stock satisfies as much of the projected demand as possible. This includes vehicles that were purchased in previous periods of the simulation and have not yet been retired. Passenger vehicles are retired based on data from the U.S. National Highway

Traffic Safety Administration (NHTSA): 10% after 5 years, 35% after 10 years, 70% after 15 years, and 100% after 20 years (Lu, 2006). Freight trucks are retired based on historical data from the Oakridge National Laboratory's transportation energy data book: 10% after 5 years, 25% after 10 years, 60% after 15 years, and 100% after 20 years (Davis et al., 2015). The remaining vehicle technologies use retirement schedules inferred from data from both the U.S. NHTSA and the Oakridge National Laboratory's transportation energy data book (Lu, 2006; Davis et al., 2015). After the existing vehicle stock has fulfilled projected demand in a given period, the available vehicle technologies (Table 2) compete for a share of the new vehicle market.

Table 2. Available vehicle technologies in CIMS-LCFS.

	Fuel Type(s) Used	*Personal Transportation Sector*			*Freight Transportation Sector*				
		Passenger Vehicles	Public Transit / Bus	Rapid Transit / Rail	Offroad	Marine	Rail	Light / Medium Truck	Heavy Truck
Diesel	Diesel: B2/R2 to B5/R5 (or B10/R10 under LCFS) or B20/R20 or R100	✓	✓	✓	✓	✓	✓	✓	✓
Gasoline	Gasoline: E5 to E10 (or to E15 under LCFS)	✓	✓					✓	
Compressed Natural Gas (CNG)	CNG		✓		✓			✓	✓
Liquefied Natural Gas (LNG)	LNG				✓	✓		✓	✓
Hybrid Electric Vehicle (HEV)	Gasoline (Personal) *or* Diesel (Freight)	✓	✓					✓	✓
Plug-In Hybrid Electric Vehicle (PHEV)	Gasoline (Personal) and Electricty *or* Diesel (Freight) and Electricity	✓						✓	
Battery Electric Vehicle (BEV)	Electricity	✓		✓	✓		✓	✓	
Fuel Cell Electric Vehicle (FCEV)	Hydrogen	✓	✓	✓	✓	✓	✓	✓	✓
Propane	Propane		✓					✓	
Flex Fuel Vehicle (FFV)	Gasoline or E85	✓							
Heavy Fuel Oil	Fuel Oil					✓			

For each vehicle type, new vehicle market share is calculated by a heterogeneous consumer market that purchases vehicles according to the CIMS market share competition algorithm (Rivers & Jaccard, 2006):

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

Equation 1 determines new vehicle market share based on consumer perceptions of each vehicle technology's life cycle cost (LCC_j) relative to the life cycle costs of all other available technologies in that subsector. A market heterogeneity behavioral parameter (v) is used to represent differences in consumer preferences and perceptions of life cycle costs for the same technology. A high value for v leads to the lowest cost technology capturing the majority of the market share, while a relatively low value for v means that the new vehicle technology market share will be spread out almost evenly between competing technologies, even if their life cycle costs differ significantly (Bataille et al., 2007). A more detailed overview of the market heterogeneity parameter can be found in Rivers and Jaccard (2005). As depicted in Table 3, I use values for v that have been empirically estimated for several sectors of the CIMS model (Horne et al., 2005; Mau et al., 2008; Axsen et al., 2009).

A vehicle technology's life cycle cost incorporates all of the perceived financial and intangible costs expected over the assumed lifespan of the vehicle:

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

A technology's life cycle cost includes its upfront capital cost (CC_j), upfront intangible cost (i_j), annual maintenance costs (MC_j), and annual energy costs (EC_j). The upfront costs are annualized over the anticipated lifespan of the vehicle (n_j) using a private discount rate (r). A private discount rate is used to represent how consumers perceive future costs (Train, 1985). A high r value translates into consumers valuing short-term benefits and costs over future benefits and costs – I use private discount rates that were empirically estimated from stated and revealed choice research (Horne et al., 2005; Mau et al., 2008; Axsen et al., 2009). Table 3 illustrates the vehicle demand parameters I use in the CIMS-LCFS model: projected travel demand growth rates, private discount rates, and market heterogeneity parameters.

Table 3. CIMS-LCFS vehicle demand parameters.

Vehicle demand parameters	**Source**	**Value (Range)**
VKT annual growth rate	U.S. EIA, 2015b	1.10%
TKT annual growth rate		1.45%
Private discount rate (r)	Axsen et al., 2009 Horne et al., 2005 Mau et al., 2008	8 – 25%
Market heterogeneity (v)		5 – 18

2.3. Declining capital and intangible costs: endogenous technological change and shifts in consumer preferences

CIMS-LCFS represents technological change through two endogenous functions. First, the declining capital cost function simulates the tendency for the capital costs of new and emerging technologies to decline as a result of manufacturer's learning by doing and economies of scale. Learning by doing is the concept that firms will reduce costs as they gain production experience, and economies of scale is the cost savings that result from scaling up production (Löschel, 2002). The declining capital cost function has two separate components for reducing the capital costs of a particular technology. First, capital costs decline endogenously as a result of an increase in the cumulative production of that technology in British Columbia. Second, capital costs decline exogenously as a result of production occurring elsewhere in the world. Therefore, a vehicle technology's capital costs can still decline over time despite little to no production occurring in British Columbia. The endogenous capital cost of a vehicle technology in a given period ($CC_j(t)$) is a function of its initial capital cost at the beginning of the simulation ($CC_j(t_0)$), the cumulative production of the technology within the model (N_j), and the technology's progress ratio (PR_j):

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

The second function simulates changes in consumer preferences as declining intangible costs. Intangible costs are non-financial factors that can affect or limit technology purchase or usage. They are estimates of consumer perceptions and preferences regarding quality, reliability, availability, and social desirability of new technologies. Intangible costs for the various vehicle technologies have been estimated through revealed and stated preference methods that quantified the effect that these perceptions and preferences have on vehicle purchase decisions (Rivers & Jaccard, 2006; Axsen et al., 2009). The declining intangible cost function has been described as the "neighbour effect", in which consumers' perceptions of a technology's non-financial costs (e.g. poor quality or lack of reliability) decline as a technology's market exposure increases (Mau et al., 2008; Axsen et al., 2009). In other words, the new technology becomes more desirable as it gains market share. The function is as follows:

$$\boldsymbol{i_j(t) = \frac{i_j(0)}{1+Ae^{k*MS_{j(t-1)}}}} \qquad \text{(Equation 4)}$$

Where the intangible cost of a technology in a given period ($i_j(t)$) is a function of its initial intangible cost (i_j), its market share in the previous period ($MS_{j(t-1)}$), and two behavioural parameters (A, k). A and k are constants that dictate the shape of the intangible cost curve and the rate at which the costs decline as a result of increased market share (Mau et al., 2008; Axsen et al., 2009).

2.4. Service costs: vehicle mode choice

In CIMS, following Figures 2 and 3, consumers are modeled to choose their mode of travel when moving from one destination to another, whether by personal vehicle, bus, rail, cycling, or walking. CIMS-LCFS allows for transport mode switching in each period in the personal transportation sector. As illustrated in Figure 2, projected personal kilometers travelled (PKT) demand in the urban travel subsector can be satisfied through four modes of travel: walking/cycling, public transit, SOV, or HOV. Similarly, projected PKT in the intercity travel subsector can be satisfied by passenger vehicles, bus, or rail. Transportation mode switching is modelled using "service costs", which are a function of the cost of the technologies within that travel mode (called price of service, PS_k) and the service requirement parameter (SR_{jk}). Since CIMS-LCFS models technology demand according to an overall "service" (e.g. PKT or VKT), the term "service costs" is used to represent an averaging of the costs based on the vehicle technology composition within each mode of travel. Recall from section 2.1. that the service requirement parameters are taken from the full CIMS model and dictate the PKT to VKT conversion. The service cost function is:

$$\boldsymbol{SC_j = \sum PS_k * SR_{jk}} \qquad \text{(Equation 5)}$$

Where the price of service for a particular travel mode (PS_k) is a function of each available vehicle technology's life cycle cost (LCC_j) and its market share in the previous period ($MS_{j(t-1)}$). Recall from section 2.2. that a technology's life cycle cost includes its capital cost, intangible costs, maintenance costs, and energy costs. The price of service function is:

$$\boldsymbol{PS_k = \sum MS_{j(t-1)} * LCC_j} \qquad \text{(Equation 6)}$$

Effectively, the price of a service (PS_k) is a weighted average of the life cycle costs ($LCCs$) of the technologies selected in that travel mode. Using an example to illustrate the role of the service cost function, the British Columbia passenger vehicle sector is currently dominated by gasoline vehicles and the public transit sector is mainly comprised of diesel buses. If the price of gasoline were to increase, the life cycle cost of each gasoline vehicle would also increase, all else held constant. The increased life cycle cost of gasoline vehicles translates into a higher service cost for any transportation mode where gasoline vehicles have a relatively high market share (e.g. passenger vehicles). Due to the increase in the service costs of passenger vehicles, some consumers will switch to other modes of travel (at a higher node), such as public transit. Since diesel vehicles currently hold a relatively large portion of the public transit market, the increase in the price of gasoline will have a relatively small effect on the service costs of public transit. Therefore, the service costs of public transit will not increase as much as the service costs of passenger vehicles. Consequently, this is will result in some consumers switching away from passenger vehicles to public transit.

2.5. Travel demand feedbacks

Simulating policy in CIMS-LCFS can cause changes to the costs consumers face relative to the reference case. In turn, consumers will adjust the amount they travel (i.e. their travel demand) in response to these changes in costs. Specifically, consumers adjust vehicle usage rates and vehicle ownership rates, through projected VKT/TKT demand, as a result of changes to the cost of driving and the purchase price of vehicles. In the existing vehicle market, vehicle usage rates respond to changes in the cost of driving (i.e. energy and maintenance costs). The inclusion of energy costs captures the rebound effect, whereby vehicle usage rates may actually increase as improved vehicle fuel efficiencies decrease energy costs (Hymel et al., 2010). In the new vehicle market, vehicle ownership rates respond to changes to the purchase price of vehicles. The magnitude of change in travel demand is determined by an elasticity parameter (e) that specifies how sensitive consumers are to changes in costs. For every 1% increase in the cost of travel, it is expected that travel demand will decrease by e%, and vice versa. The travel demand feedback function is incorporated into the passenger vehicle sector and the freight truck sector for both vehicle usage rates and vehicle ownership rates. Elasticity parameters are taken from literature and depicted in Table 4. Equation 7 illustrates that the amount of projected travel demand in the policy scenario (D_{POL}) is a function of the projected travel demand in the reference case (D_{REF}), the elasticity parameter (e), and the changes to the cost of travel in the policy scenario relative to the reference case:

$$\boldsymbol{D_{POL}(t) = D_{REF}(t) * e * \frac{(\sum C_{jREF} * MS_{jREF} - \sum C_{jPOL} * MS_{jPOL})}{\sum C_{jREF} * MS_{jREF}}} \qquad \text{(Equation 7)}$$

Table 4. CIMS-LCFS travel demand feedback elasticities

Vehicle market	**Passenger vehicles**	**Light/medium freight trucks**	**Heavy freight trucks**
Existing vehicle market: vehicle usage rates	-0.20[*]	-0.51[***]	-0.51[***]
New vehicle market: vehicle ownership rates	-0.55[**]	-1.06[***]	-1.31[***]

[*] Small & Ven Dender, 2007
[**] Fouquet, 2012
[***] Beuthe et al., 2001

2.6. Fuel switching for multi-fuel capable vehicles

Some of the vehicle drivetrains that I model in CIMS-LCFS are multi-fuel capable – providing consumers the flexibility to choose between different fuels based on relative costs. Specifically, flex fuel vehicles (FFVs) have an internal combustion engine that is capable of operating on gasoline or any blend of gasoline and ethanol up to E85 (85% ethanol, 15% gasoline) (U.S. DOE, 2016a). Additionally, conventional compression ignition internal combustion engines are capable of operating on diesel or a variety of blends of diesel and biodiesel or HDRD. Similar to E85, these blends are commonly denoted by their renewable content portion: B20 is 20% biodiesel and 80% diesel, R20 is 20% HDRD and 80% diesel, and R100 is 100% HDRD. Approximately 70% of the major diesel engine manufacturers that operate in the United States have approved the use of B20 (e.g. 20% biodiesel, 80% diesel) in their engines, with the remaining 30% approving B5 (National Biodiesel Board, 2016). Previous literature examining engine performance and wear in compression ignition engines found that B20 can be used with little to no engine modifications (Murugesan et al., 2009; Buyukkaya, 2010; Özener et al., 2014).

Ethanol, biodiesel, and HDRD all have lower energy densities than their petroleum alternatives. Meaning, one tank of a renewable fuel blend – E85, B20/R20, or R100 – cannot travel as far as one tank of petroleum gasoline or diesel. For example, ethanol contains approximately 68% of the energy of gasoline; meaning, one litre of E85 yields about 75% of the energy as one litre of E10 gasoline (Government of B.C., 2016a). Therefore, the cost of driving per km is only equivalent when E85 is priced about 20 to 25% below E10 gasoline. Consequently, my model does not experience substantial fuel switching until the price of E85 falls about 15 to 20% below the price of gasoline. In contrast, biodiesel and HDRD contain approximately 95% of the energy of petroleum diesel (Government of B.C., 2016a). Thus, for biodiesel- and HDRD-blended fuels, the difference in the cost of driving per km is negligible when the renewable fuels and diesel are priced the same. However, there are other factors besides monetary costs that dictate consumers' choice of fuel in my model, as discussed in the next paragraph.

In each period, I model consumers' choice of fuel for their FFVs and diesel engines through a heterogeneous consumer market that uses fuel according to a market share competition:

$$\boldsymbol{MS_F = \frac{(EC_F + i_F)^{-v}}{\sum(EC_K + i_K)^{-v}}} \qquad \text{(Equation 8)}$$

The market share of each fuel blend (MS_F) is determined by its energy cost (EC_F) and its intangible cost (i_F). The energy cost parameter accounts for the lower energy content of the renewable fuel blends through relative vehicle fuel efficiencies. A market heterogeneity parameter (v) is used because some consumers are willing to pay a premium for renewable fuel blends based on preferences regarding environmental concerns and energy security (Salvo & Huse, 2011; Anderson, 2012). An intangible cost is applied to the renewable fuel blends – E85, B20/R20, and R100 – on the basis of their limited availability at retail locations. In the United States, approximately 2% of retail locations offer E85, with the majority (64%) located in the U.S. Midwest (U.S. DOE, 2017). In British Columbia, the only retail station offering E85 fuel, aimed at racing enthusiasts, closed in early October 2016 (Arcade Station, 2016). Research suggests that the lack of availability of mid- to high-level renewable blends is a barrier to further growth in demand for these fuels (Greene et al, 2009; Liu & Greene, 2014). I model the implied cost of the limited availability of renewable fuel blends based on the equation developed by Liu & Greene (2014):

$$\boldsymbol{\$/gallon\ penalty = -2.04e^{-39.57*\%E85}} \qquad \text{(Equation 9)}$$

The dollar per gallon penalty is a function of the percentage of fuel stations offering E85 ($\%E85$), which was found to be negligible when E85 was available at approximately 15% of retail locations in Minnesota (Liu & Greene, 2014). Also, I model fuel retailers as responding to biofuel demand by increasing or decreasing the availability of mid- and high-level renewable fuel blends at retail locations based on the previous period's demand for the blends relative to petroleum gasoline and diesel. For example, if consumers demand 5,000 litres of E85 and 100,000 litres of gasoline in a given period, the percentage of fuel stations offering E85 the following period will be 5% (=5,000/100,000).

In this study, I assume that renewable fuel blends – E85, B20/R20, and R100 – are only available to the market (in any capacity) in the policy scenarios that include a LCFS. In other words, these mid- and high-level renewable fuel blends have zero market share in any non-LCFS scenarios. Ethanol, biodiesel, and HDRD are generally more expensive than gasoline and diesel. In Western Canada, there are currently zero retail fuelling stations offering mid- and high-level renewable fuels (personal communication, 2016). Given the historic lack of availability in British Columbia (and in Canada), the lower energy content of the renewable fuel blends, and their cost premium over petroleum fuels, there is little incentive for fuel suppliers to offer these fuels without energy or climate policy. The LCFS provides an incentive for fuel suppliers to supply renewable fuel blends because they can generate compliance credits that have an established market value.

Further, I assume that the demand for high-level blends (R100) can only be fulfilled using hydrogenation-derived renewable diesel (HDRD). This is in contrast to the demand for mid-level blends, which can be satisfied with either biodiesel (i.e. B20) or HDRD (i.e. R20). Compared to biodiesel, HDRD has a higher cetane number, performs better in cold weather conditions, and is generally better suited for use in modern diesel engines at higher concentrations (Aatola et al., 2008; Knothe, 2010; Lapuerta et al., 2011; Kim et al., 2014). Chemically, HDRD is comprised of hydrocarbons that are nearly identical to conventional diesel (Aatola et al., 2008; NRC, 2012). Moreover, HDRD has a higher cetane number than diesel, but a lower energy density (Aatola et al., 2008; Government of B.C., 2016a). Blending HDRD with diesel at higher concentrations can create a fuel blend that is of premium grade; meaning, the cetane number is increased and aromatic content is decreased which leads to lower exhaust emissions and better cold-start performance compared to conventional diesel (Aatola et al., 2008). Further, a compression ignition diesel engine has the potential to run on 100% HDRD with little to no modifications (Aatola et al., 2008; Lapuerta et al., 2011; Nylund et al., 2011). Nylund et al. (2011) demonstrated the viability of using R100 HDRD in unmodified compression ignition engines; other studies suggest that minor adjustments to the valve and injection timing of the engine would be necessary to account for HDRD's lower energy density and higher cetane number (Aatola et al., 2008; Lapuerta et al., 2011). Evidence from the first few years of British Columbia's LCFS indicates that fuel suppliers are willing to blend HDRD at higher concentrations compared to biodiesel (B.C. MEM, 2016b).

2.7. Fuel supply optimization model: aggregate fuel supply decisions under a LCFS policy

The fuel supply optimization model contains ten transportation fuels available to the British Columbia transportation sector: biodiesel, diesel, electricity, ethanol, gasoline, hydrogen, LNG, CNG, propane, and HDRD. The available fuels are further broken down by their respective feedstock sources, each having its own associated production cost and carbon intensity. The production costs of the various fuels are largely informed from Cazzola et al. (2013), with additional literature used to estimate the production costs of emerging alternative fuels (see Table 5). At the beginning of a simulation, the available fuels have an initial production cost that declines endogenously through the declining fuel production cost function (see section 2.8.). Carbon intensity values for ethanol, biodiesel, and HDRD are based on a weighted average of the registered fuel codes in British Columbia (B.C. MEM, 2016a). Specifically, I use the respective nameplate capacities of the various alternative fuel production facilities to calculate the weighted average carbon intensity values. The remaining fuels are estimated using either the GHGenius model, the GREET model, or from literature. GHGenius 4.03a was used where possible, because it is the current approved model for calculating carbon intensities under British Columbia's LCFS, as of the writing of this research report (B.C. MEM, 2014). The GREET model or literature was used in those cases where the established fuel pathway was not readily available in GHGenius 4.03a, such as for renewable CNG and cellulosic ethanol. While GHGenius may be able to model these pathways through modifying certain parameters in the model, readily available published values from either California's LCFS (e.g. from GREET) or literature were used instead. Table 5 illustrates the types of fuel and feedstocks available in the fuel supply optimization model including their respective production costs and assumed carbon intensities.

Table 5. Fuel supply optimization model inputs

Fuel	**Fuel Source**	**Production Costs ($CAD/GJ)**			**Carbon Intensity**	
		Initial Cost	**Mature Tech Cost**	**Source(s)**	**(gCO2e/MJ)**	**Source(s)**
Biodiesel	Corn	22.08	19.65	Cazzola et al., 2013	18.79	Weighted average*
	Palm	18.06	16.01	Ong et al., 2012; Cazzola et al., 2013	57.91	Weighted average*
	Tallow†	18.50	16.39	Milbrandt & Overend, 2008; Cazzola et al., 2013	3.11	Weighted average*
	Canola	22.08	19.57	Milbrandt & Overend, 2008; Cazzola et al., 2013	15.84	Weighted average*
	Soy	19.04	16.88	Ong et al., 2012; Miller, 2012; Cazzola et al., 2013	16.29	Weighted average*
	Carinata	24.51	18.22	Milbrandt & Overend, 2008; Cazzola et al., 2013	10.67	Weighted average*
	Yellow Grease†	20.11	17.82	Milbrandt & Overend,	6.21	Weighted average*

				2008; Ong et al., 2012; Cazzola et al., 2013		
	Camelina†	24.51	17.82	Milbrandt & Overend, 2008; Cazzola et al., 2013	21.87	Weighted average*
Diesel		16.00	16.00	Cazzola et al., 2013	94.76	GHGenius 4.03a
Electricity		28.50	22.59	Cazzola et al., 2013	19.73	GHGenius 4.03a
Ethanol	Wheat	26.43	19.50	Milbrandt & Overend, 2008; Cazzola et al., 2013	35.40	Weighted average*
	Corn	26.43	19.50	Cazzola et al., 2013	52.27	Weighted average*
	Sugarcane†	19.90	18.00	Cazzola et al., 2013	37.24	Weighted average*
	Cellulosic†	33.19	23.50	Cazzola et al., 2013	1.60	GREET
Gasoline		16.00	16.00	Cazzola et al., 2013	88.14	GHGenius 4.03a
Hydrogen	Natural Gas Reformation	98.39	24.50	Cazzola et al., 2013	51.99	GHGenius 4.03a
	Electrolysis†	128.21	31.93	Genovese, 2009; Dillich et al., 2012; Cazzola et al., 2013	37.43	GHGenius 4.03a
	Waste Hydrogen Capture†	128.21	31.93	Genovese, 2009; Dillich et al., 2012; Cazzola et al., 2013	11.00	GHGenius 4.03a
Natural Gas	Fossil-based CNG	14.73	9.50	U.S. DOE, 2015; Cazzola et al., 2013	62.14	GHGenius 4.03a
	Renewable CNG†	19.15	12.35	Malins et al., 2015; Cazzola et al., 2013	12.36	Average value from CARB lookup table (GREET)
	Fossil-based LNG	21.42	18.20	Cazzola et al., 2013	63.26	GHGenius 4.03a
	Renewable LNG†	27.84	23.66	Malins et al., 2015; Cazzola et al., 2013	22.05	Average value from CARB lookup table (GREET)
Propane		18.88	18.88	U.S. DOE, 2015; U.S. EIA, 2015a	67.65	GHGenius 4.03a
HDRD	Palm	19.87	17.68	Cazzola et al., 2013	53.70	Weighted average*
	Tallow†	20.35	18.11	Cazzola et al., 2013	31.45	Weighted average*
	Canola†	27.46	21.42	Miller, 2012	38.97	Weighted average*
	Soy†	20.95	18.64	Cazzola et al., 2013	47.91	Weighted average*
	Camelina†	27.96	21.81	Miller, 2012	30.00	Miller, 2012
	Yellow Grease†	22.12	16.69	Cazzola et al., 2013	16.39	Weighted average*
	Corn†	26.96	21.03	Cazzola et al., 2013	31.27	Weighted average*

† contains high cost version of fuel due to limited availability

* weighted average of all registered fuel codes in British Columbia ("weighted" based on nameplate capacity of registered facilities)

The fuel supply optimization model contains a total of 50 constraints that can be separated into four categories: fuel demand, fuel availability, technical, and policy constraints. First, for petroleum gasoline and diesel, the fuel demand constraints stipulate that fuel suppliers must supply the entire quantity of gasoline and diesel demanded by consumers in CIMS-LCFS. Recall that the fuel supply optimization model is designed to be a representation of petroleum fuel suppliers' decision-making at the aggregate level. For alternative fuels, fuel suppliers can supply any quantity up to and including the amount demanded by consumers in CIMS-LCFS, subject to constraints regarding fuel availability (discussed below).

The second constraint category is fuel availability, which limits the volumes of particular emerging alternative fuels to the British Columbia marketplace at their initial production costs. Emerging fuel technologies, such as cellulosic ethanol and hydrogen from electrolysis, are either in the early stages of development or are currently too expensive for widespread commercialization; thus, I model supply to be limited in the early periods of the simulations. In other cases, it is the feedstock used to produce the alternative fuel that is available in limited quantities; this is the case for renewable CNG, renewable LNG, tallow-, and yellow grease-based biodiesel or HDRD. I use values estimated from literature to limit the quantity of each emerging fuel in a given simulation period (E2 Entrepreneurs, 2014; Malins et al., 2015; USDA, 2015). If an emerging fuel's limited availability constraint becomes binding during a simulation, the model will offer additional supply of that alternative fuel, albeit at a significantly higher cost. My method for limiting the availability of emerging fuels can be thought of as a two-step cost curve: first, there is the initial supply available at the market price; if that supply becomes exhausted in a given period, there are additional quantities available at a considerably higher price. With other jurisdictions – California, Oregon, United States, Brazil, and the European Union – competing for access to low carbon fuels, the costs of acquiring additional quantities of emerging fuels increases. Table 5 indicates the fuels that have limited quantities available at their initial production cost.

Third is the technical constraint category, which stems from the idea, whether real or perceived, that there exists a "blend wall" for renewable fuel blending. The "blend wall" is the maximum volume of ethanol or biodiesel that can be blended for use in conventional gasoline or diesel engines, respectively. Historically, the amount of ethanol that could be blended into gasoline was limited to 10% by volume under the guidance of the U.S. Environmental Protection Agency (EPA), as well as by automaker vehicle and engine warranties (Yacobucci, 2009). For biodiesel blending, the perceived "blend wall" has been noted to be 5% by volume. The U.S. EPA has since issued a waiver allowing E15 to be used in light-duty vehicles with a model year of 2001 or newer (U.S. EPA, 2016). Additionally, many auto manufacturers have now approved the use of E15 in their warranty statements (RFA, 2015). As previously mentioned, approximately 70% of the major diesel engine manufacturers that operate in the United States have now approved the use of B20 (i.e. 20% biodiesel, 80% diesel) in their engines (National Biodiesel Board, 2016). In the fuel supply optimization model, I set the "blend wall" constraint at a conservative 10% for ethanol in gasoline and 5% for biodiesel in diesel. I assume that in the absence of a LCFS the initial "blend wall" remains unchanged. However, in the policy scenarios that contain a LCFS, I relax the constraint in 2025 to allow for 15% ethanol in gasoline and 10% biodiesel in diesel. The "blend wall" then remains unchanged for the rest of the simulation – however, it is technically feasible that future gasoline and diesel drivetrains could be designed to effectively consume mid- and high-level biofuel blends.

The final constraint category is policy constraints, where I use three policy constraints to represent the two distinct portions of British Columbia's LCFS: (1) the Renewable Fuel Requirement, and (2) the Low Carbon Fuel Requirement. First, the Renewable Fuel Requirement requires a minimum percentage of renewable fuel in relation to the petroleum fuel supplied in the compliance period. Specifically, it calls for a province-wide average of 5% by volume in relation to the petroleum gasoline supplied (i.e. ethanol) and 4% by volume in relation to the petroleum diesel supplied (i.e. biodiesel or HDRD). The requirement can be met by blending renewable fuels into petroleum gasoline or diesel, supplying mid-level blends (i.e. B20/R20), or supplying high-level blends (i.e. R100, E85). Second, the Low Carbon Fuel Requirement prescribes a carbon intensity limit that decreases each year until it becomes 10% less than the carbon intensity of petroleum gasoline or diesel in 2020 (Government of B.C., 2008). In a given compliance period, supplying a fuel with a carbon intensity above the prescribed carbon intensity limit incurs debits (e.g. gasoline and diesel) while supplying a fuel with a carbon intensity below the prescribed carbon intensity limit generates credits (e.g. electricity). To comply with the Low Carbon Fuel Requirement, a fuel supplier must ensure that the sum of its credits is greater than or equal to the sum of its debits. For a single fuel in a given compliance period, the amount of credits generated or debits incurred is determined by the following formula:

$$\boldsymbol{Credit\ (or\ Debit)_{F_n} = (CI\ limit * EER - CI\ fuel) * EC\ fuel/1{,}000} \qquad \text{(Equation 10)}$$

The resulting quantity of credits or debits from the supply of a single fuel (F_n) is a function of the prescribed carbon intensity limit for the compliance year for the class of fuel of which the fuel is a part ($CI\ limit$), the prescribed energy effectiveness ratio (EER), the carbon intensity of the fuel supplied ($CI\ fuel$), and the energy content of the fuel supplied in gigajoules ($EC\ fuel$). The EER is a unit-less factor that accounts for differences in energy efficiency between the different types of transportation fuels and vehicles (CARB, 2009). EERs are defined as the ratio of the number of kilometers driven per unit energy consumed for a particular fuel to the kilometers driven per unit energy for a reference fuel (CARB, 2009). In the case of British Columbia's LCFS, the reference fuels are gasoline for light-duty vehicles and diesel for heavy-duty vehicles. As an example, electric vehicles are more efficient relative to gasoline vehicles in terms of kilometers driven per unit energy consumed. Thus, electricity used as a transportation fuel in replacement of gasoline has an EER of 2.7 (Government of B.C., 2016a). For each fuel supplied in the fuel supply optimization model, equation 10 calculates the number of credits generated or debits incurred in that period. The carbon intensity constraint is then:

$$\boldsymbol{Credit\ (or\ Debit)_{F_1} + Credit_{F_2} + \cdots + Credit_{F_n} \geq 0} \quad \text{(Equation 11)}$$

Equation 11 stipulates that the total credits and debits generated from the supply of fuel in a given period must be greater than or equal to zero. When combined, equation 10 and equation 11 satisfy the Low Carbon Fuel Requirement by ensuring that the sum of the credits generated from the supply of fuel in a given period is equal to or greater than the sum of the debits incurred from the supply of fuel in British Columbia. If the Low Carbon Fuel Requirement constraint cannot be satisfied in a given period, the simulation will fail and that particular policy scenario will be considered “infeasible” under the assumed parameters and constraints.

2.8. Declining fuel production costs: endogenous technological change

Similar to the declining capital cost function described for CIMS-LCFS in section 2.3., the declining fuel production cost function allows the production costs of certain fuel technologies to decline as a result of learning by doing and economies of scale (Löschel, 2002). The declining fuel production cost function has two separate components for reducing the production cost of a particular transportation fuel. First, fuel production costs decline endogenously as a result of an increase in the cumulative production of that fuel in British Columbia. Second, fuel production costs decline at an exogenous rate as a result of production occurring elsewhere in the world. Therefore, fuel production costs can still decline even when the fuel is not supplied to the British Columbia marketplace. The endogenous production cost of a transportation fuel in a given period ($PC_j(t)$) is a function of its initial production cost at the beginning of the simulation ($PC_j(t_0)$), the cumulative production of the transportation fuel within the model (N_j), and the fuel’s progress ratio (PR_j):

$$\boldsymbol{PC_j(t) = PC_j(t_0)\left(\frac{N_j(t)}{N_j(t_0)}\right)^{log_2 PR_j}} \quad \text{(Equation 12)}$$

The fuel progress ratios (Table A.1. in the Appendix) and the initial cumulative production values are informed from literature (Greaker et al., 2008; Schoots et al., 2008; De Wit et al., 2010; Chen et al., 2012). A minimum production cost for each fuel sets the lower bound on the level of cost reductions that are achievable (Table 5 – Mature Tech Cost). The values I use are informed from the mature technology scenario described in Cazzola et al. (2013), in which the authors examined the potential for cost reductions under the assumption of a fully developed independent supply chain. An additional feedback mechanism reduces the end-use price of a fuel within CIMS-LCFS as its production costs decline in the fuel supply optimization model. I assume that any cost reductions achieved in the fuel supply optimization model are fully passed on to consumers in CIMS-LCFS in the form of lower end-use energy prices.

2.9. Energy price and GHG assumptions

CIMS-LCFS contains nine base fuels: gasoline, diesel, ethanol, biodiesel/HDRD, propane, natural gas, electricity, hydrogen, and heavy fuel oil. The price schedules for petroleum gasoline and diesel are exogenously set and do not change during the simulation (other than changes due to carbon pricing). Each alternative fuel is defined by a set of exogenous baseline price schedules, which can then be endogenously influenced by the declining fuel production cost function. Energy costs in each period are a product of vehicle fuel efficiency, assumed VKT or TKT per vehicle per year, and fuel prices. Vehicle fuel efficiency is set exogenously depending on the stringency of the vehicle GHG standard (i.e. the CAFE standard), which I describe in section 2.10. The assumed VKT or TKT per vehicle per year was taken directly from the full CIMS model and varies widely across each sector. The baseline price schedules for gasoline, diesel, natural gas, and electricity are taken from the National Energy Board's (NEB's) *Canada Energy Futures 2016* forecasts to 2040. Ethanol and propane price schedules are based on the U.S. EIA's Annual Energy Outlook 2016 forecasts to 2050; biodiesel and HDRD are inferred from the U.S. Department of Energy's (DOE) clean cities report; and hydrogen and marine heavy fuel oil prices are taken from the full CIMS model.

Table 6. Baseline end-use fuel price schedule for British Columbia ($CAD/GJ)

Fuel	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gasoline	34.56	39.30	41.32	43.31	44.22	45.25	46.38	47.54
Diesel	35.44	40.64	42.93	45.16	46.21	47.39	48.57	49.79
Ethanol	39.42	36.95	33.00	34.91	36.64	36.18	35.50	35.27
Biodiesel/HDRD	45.13	50.97	53.23	55.13	53.56	50.76	49.96	49.22
Propane	25.09	27.37	28.11	28.99	30.19	31.49	32.27	33.08
Natural Gas	13.21	13.74	13.55	13.33	13.13	12.93	12.70	12.54
Electricity	27.41	28.63	28.78	28.93	29.07	29.22	29.36	29.51
Hydrogen	41.21	36.52	34.29	32.21	30.27	28.47	26.79	25.22
Heavy Fuel Oil	15.26	15.92	16.49	16.95	17.29	18.66	20.03	21.41

Sources:
Gasoline, Diesel, Natural Gas, Electricity: *Canada Energy Futures 2016*
Ethanol, Propane: *AEO 2015*
Biodiesel/HDRD: US DOE Jan 2016 Report
Hydrogen, Heavy Fuel Oil: Full CIMS model

I calculate the well-to-wheel (WTW) GHG emissions from the British Columbia transportation sector from the quantity of each fuel consumed in a given period and their respective carbon intensity values. For petroleum gasoline and diesel, the carbon intensity values were determined using British Columbia's approved version of GHGenius (4.03) for calculating the carbon intensities of transportation fuels under the LCFS (B.C. MEM, 2014). In the policy scenarios that contain a LCFS, the carbon intensities used to calculate WTW GHG emissions are listed in the fuel supply optimization input table (Table 5). Refer to section 2.7. for a more detailed description of the methodology for determining those values. In the policy scenarios that do not include a LCFS, I use a variation of the default carbon intensity values assigned under British Columbia's LCFS to calculate WTW GHG emissions. For some fuels, the default value represents the carbon intensity of the fuel produced using mature production methods. For example, the default value for hydrogen assumes that the fuel is produced in British Columbia using natural gas reformation, which is the process used to produce 95% of the hydrogen consumed in the United States (U.S. DOE, n.d.). For the renewable biomass-based fuels – ethanol, biodiesel, and HDRD – the default values represent the lower cost, higher carbon intensity feedstocks. In other words, I assume that absent a LCFS, British Columbia fuel suppliers will seek to comply with the federal renewable fuel regulation by supplying the lowest cost renewable fuels regardless of carbon intensity. The supply of lower cost, higher carbon intensity renewable fuels has been observed in the early reporting-only stages of British Columbia's LCFS, prior to the Low Carbon Fuel Requirement coming into effect (B.C. MEM, 2016b). For propane, I assume that the fuel is sourced from 90% natural gas processing facilities and 10% petroleum refineries, determined using Western Canadian propane production and supply data from Statistics Canada (Government of Canada, 2013).

Table 7. Default carbon intensity values

Fuel	**Carbon Intensity (gCO_2e/MJ)**
Biodiesel & HDRD	94.76
Diesel	94.76
Electricity	19.73
Ethanol	88.14
Gasoline	88.14
Hydrogen	96.82
Natural Gas (CNG)	63.64
Natural Gas (LNG)	65.14
Propane	67.65

Sources: Government of B.C., 2016a; Government of Canada, 2013

2.10. Policy scenarios and assumptions

To achieve my research objectives, I simulate a base case, a reference case, and a series of policy scenarios. The base case does not contain any climate policies and is used to set the baseline for the travel demand feedback function (described in section 2.5.). The reference case is used to calibrate the model and is designed to mirror the current policy environment in British Columbia. Vehicle technology market shares and total VKT/TKT demand are calibrated to *AEO2015's Reference Case* (U.S. EIA, 2015b); total energy use in the British Columbia transportation sector is calibrated to *Canada Energy Futures* projected forecast (NEB, 2016); and tailpipe GHG emissions are calibrated based on NRCan's historical data (NRCan, n.d.) and *AEO2015's Reference Case* (U.S. EIA, 2015b). Calibration was achieved by making adjustments to the capital cost and intangible cost parameters.

My research objectives focus on the LCFS, and therefore, I simulate five LCFS policies of varying stringency. The LCFS scenarios are intended to cover the full spectrum of potential carbon intensity reduction targets to 2050. As illustrated in Table 8 below, "B.C. Reference case" scenario follows the initial British Columbia LCFS reduction target schedule by requiring a 10% reduction in the carbon intensity of transportation fuels by 2020, then maintaining that 10% reduction per period out to 2050. The "Low stringency" scenario mirrors the recent 2016 British Columbia Climate Leadership Plan which recommends a 15% reduction by 2030 (Government of B.C., 2016b), then assuming that the target increases to 25% by 2050. The "Medium stringency" scenario follows the British Columbia Climate Leadership Team's initial recommendation of a 20% reduction by 2030 (CLT, 2015) and the "High stringency" scenario requires a 75% reduction by 2050.

Table 8. British Columbia LCFS target scenarios (% of carbon intensity reductions; gCO_2e/MJ)

	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Scenario 0: No LCFS	-	-	-	-	-	-	-	-
Scenario 1: BC Reference Case	2.5%	10%	10%	10%	10%	10%	10%	10%
Scenario 2: Low stringency	2.5%	10%	12.5%	15%	17.5%	20%	22.5%	25%
Scenario 3: Medium stringency	2.5%	10%	15%	20%	25%	30%	35%	40%
Scenario 4: High stringency	2.5%	10%	20%	30%	42.5%	55%	65%	75%

The LCFS scenarios are accompanied with three distinct "non-LCFS" policy packages – Weak, Moderate, Ambitious – that include four different policies of various stringencies. The policies and their stringency levels are summarized in Table 9, which I break up by policy type here:

1. **The carbon tax** in the "Weak" policy package mirrors British Columbia's current tax which is frozen at $30 per tonne carbon dioxide equivalent (tCO_2e). Reflecting the actual carbon tax in British Columbia as of 2017, this Weak scenario models the tax as being charged at a set rate for all transportation fuels, with gasoline/ethanol and diesel/biodiesel/HDRD being charged at a set rate regardless of differences in carbon intensity (that is, the carbon tax is not applied based on well-to-wheel emissions of biofuels). For the Moderate and Ambitious policy packages, the carbon tax charge is applied to each eligible transportation fuel based on their respective WTW GHG emissions. The carbon tax in the Moderate policy package steadily rises to $118/$tCO_2e$ by 2050, and the Ambitious policy package includes a carbon tax that reaches $350/$tCO_2e$ by 2050. The Ambitious carbon tax is based on the Bataille et al. (2015) study titled *Pathways to Deep Decarbonization in Canada*, where the authors explored policy packages consistent with limiting global mean temperature to an increase of two degrees Celsius.
2. **The vehicle GHG standard (e.g. CAFE standard)** is based on United States Corporate Average Fuel Economy (CAFE) standards that are designed to reduce energy consumption by requiring auto manufacturers to improve the fuel economy of their vehicle fleets each year (NHTSA, 2016). I model a CAFE-like standard for British Columbia by exogenously improving the fuel economy of the various vehicle technologies over the entire simulation period. Unlike the current fuel

economy policies in Canada and the U.S., I extend the vehicle GHG standard to cover a wide variety of sectors in CIMS-LCFS: passenger vehicles, light/medium and heavy freight trucks, public transit and intercity buses, marine freight, offroad vehicles, and rail freight. I simulate different levels of CAFE stringency for the three policy packages. The marine freight fuel efficiency improvements are based on expected ship efficiency increases resulting from the implementation of mandatory regulations on Energy Efficiency for Ships in MARPOL Annex VI (U.S. EIA, 2015c). I use this as my starting point for the Weak policy package where ship efficiency is expected to improve an average of 1 percent per year (U.S. EIA, 2015c). Rail freight efficiency improvements are based on a technical assessment done by the U.S. Department of Transportation in their published study *Best Practices and Strategies for Improving Rail Energy Efficiency* (U.S. DOT, 2014). For medium- and heavy-duty freight trucks, the Weak policy scenario incorporates expected fuel efficiency improvements from the currently implemented heavy-duty CAFE standard (U.S. EIA, 2015b). For the Moderate and Ambitious policy packages, I base fuel efficiency improvements on the International Council on Clean Transportation's (ICCT) study that estimated the potential fuel efficiency improvements from technology that is either already commercialized or has been demonstrated to be commercially available by the 2030 timeframe (Delgado et al., 2016). For the remaining sectors, fuel efficiency improvements for the Weak policy package are based on existing U.S. CAFE policy and informed from *AEO2015's Reference Case* (U.S. EIA, 2015b). The improvements in the Moderate and Ambitious policy scenarios are informed from the National Research Council's (NRC) book *Transitions to Alternative Vehicles and Fuels* (NRC, 2013).

3. **The zero emission vehicle (ZEV) mandate** requires auto manufacturers to sell an increasing percentage of ZEV vehicles per year (Collantes & Sperling, 2008). I model a technology-neutral ZEV in the Moderate and Ambitious scenarios by requiring specified market share percentages be met with any combination of the vehicles I classify as zero emission (see Table A.2. in the Appendix). The ZEV mandate is applied to the passenger vehicle sector, the light/medium freight truck sector, and the heavy freight truck sector. For passenger vehicles and light/medium freight trucks, I allow plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and hydrogen fuel cell electric vehicles (FCEVs) to equally satisfy the ZEV mandate. In addition, unlike the California and Quebec ZEV mandates, I include flex fuel vehicles (FFVs) as an eligible technology to satisfy the ZEV requirement in the passenger vehicle sector. Although FFVs are not necessarily zero emission vehicles, they have the potential to reduce emissions if they consume mid- to high-level ethanol blends from lower carbon sources. Within the heavy truck freight sector, FCEVs are the only vehicle technology capable of satisfying the ZEV mandate requirements. While BEVs can play a role in reducing emissions in the light/medium freight sector, current battery technology does not allow for moving large amounts of goods over

long distances (den Boer et al., 2013; Fulton & Miller, 2015). Several studies that have assessed potential low carbon options for freight trucks have found that battery electric technology would need to progress substantially before becoming a viable option for heavy-duty trucks (den Boer et al., 2013; Fulton & Miller, 2015). Additionally, R100-capable vehicles do not count for compliance with the ZEV requirement for heavy freight trucks. In my model, conventional diesel engines are capable of running HDRD-based R100 with little to no modification. At the beginning of the simulation, the heavy freight truck sector is dominated almost entirely by diesel engines. Therefore, allowing R100-capable vehicles would result in even the most stringent ZEV requirement being satisfied immediately by the existing diesel vehicle fleet.

4. **The ZEV purchase subsidy** is based on British Columbia's Clean Energy Vehicle program (CEVforBC) and provides vehicle point-of-sale incentives only for passenger battery electric and hydrogen fuel cell vehicles (Government of B.C., n.d.). Specifically, CEVforBC provides $2500 to $5000 off of the purchase price of PHEVs and BEVs, and $6000 off of FCEVs (Government of B.C., n.d.). For the Weak policy scenario, I assume the policy runs until its currently scheduled end date of 2018 (Government of B.C., n.d.). For the Moderate and Ambitious policy scenarios, I extend the CEVforBC program until 2025 and 2030, respectively.

Table 9. Scenarios for "Non-LCFS" policy packages (Weak, Moderate, and Ambitious)

Scenarios for "Non-LCFS" policies	**Stringency**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Weak Policy Package	Carbon Tax ($/t$CO_2$e)	$30	$30	$30	$30	$30	$30	$30	$30
	Passenger Vehicle CAFE standard (% reduction in GJ/km from 2015)[1]	-	17%	33%	34%	34%	34%	34%	34%
	Heavy Freight CAFE standard (% reduction in GJ/km from 2015)[2]	-	10%	13%	13%	14%	14%	14%	14%
	ZEV mandate (% of new vehicle sales)[3]	0%	0%	0%	0%	0%	0%	0%	0%
	ZEV subsidy ($/vehicle)[4]	$5000 / $6000	$5000 / $6000	-	-	-	-	-	-
Moderate Policy Package	Carbon Tax ($/t$CO_2$e)[5]	$30	$43	$55	$68	$80	$93	$105	$118
	Passenger Vehicle CAFE standard (% reduction in GJ/km from 2015)[1]	-	17%	33%	42%	46%	50%	54%	57%
	Heavy Freight CAFE standard (% reduction in GJ/km from 2015)[2]	-	10%	13%	16%	21%	26%	32%	37%
	ZEV mandate (% of new vehicle sales)[3]	3%	12%	20%	25%	35%	45%	55%	65%
	ZEV subsidy ($/vehicle)[4]	$5000 /	$5000 /	$5000 /	-	-	-	-	-

		$6000	$6000	$6000					
Ambitious Policy Package	Carbon Tax ($/t$CO_2$e)[5]	$30	$50	$100	$150	$200	$250	$300	$350
	Passenger Vehicle CAFE standard (% reduction in GJ/km from 2015)[1]	-	17%	33%	49%	53%	57%	61%	65%
	Heavy Freight CAFE standard (% reduction in GJ/km from 2015)[2]	-	10%	16%	24%	32%	41%	48%	57%
	ZEV mandate (% of new vehicle sales)[3]	3%	14%	25%	30%	40%	60%	80%	100%
	ZEV subsidy ($/vehicle)[4]	$5000 / $6000	$5000 / $6000	$5000 / $6000	$5000 / $6000	-	-	-	-

[1] CAFE standard improvements in passenger vehicle fuel economy are for gasoline drive trains. With the Reference Case CAFE: diesel engines, FFVs, and HEVs are approximately 20 to 25% more efficient from 2025 onward; PHEVs are approximately 16% more efficient; and, BEVs and FCEVs are approximately 5% more efficient from 2025 onward. With the Moderate policy package: diesel engines, FFVs, and HEVs follow the same trajectory as gasoline vehicles; PHEVs are approximately 40% more efficient by 2050; and, BEVs and FCEVs are approximately 35 to 40% more efficient by 2050. With the Ambitious policy package: diesel engines, FFVs, and HEVs follow the same trajectory as gasoline vehicles; PHEVs are approximately 50% more efficient by 2050; and, BEVs and FCEVs are approximately 45 to 50% more efficient by 2050.

[2] CAFE standard improvements in freight vehicle fuel economy are for diesel drive trains. With the Reference Case CAFE: gasoline engines follow the same trajectory as diesel vehicles; propane, CNG, and LNG vehicles are approximately 8 to 10% more efficient from 2025 onward; and, BEVs, FCEVs, HEVs, and PHEVs do not improve in efficiency relative to 2015. With the Moderate policy package: gasoline engines, propane, CNG, and LNG follow the same trajectory as diesel vehicles; and, BEVs, FCEVs, HEVs, and PHEVs are 16% more efficient by 2050. With the Ambitious policy package: gasoline engines, propane, CNG, and LNG follow the same trajectory as diesel vehicles; and, BEVs, FCEVs, HEVs, and PHEVs are 45% more efficient by 2050.

[3] ZEV mandate is applied to the passenger vehicle sector, the light/medium freight truck sector, and the heavy duty freight truck sector.

[4] ZEV subsidy covers $5000 for BEVs and $6000 for FCEVs in the passenger vehicle sector.

[5] Carbon tax applied based on each fuel's WTW GHG emissions.

The policy scenarios listed in Table 9 were developed to explore my research objectives and focus on three important model outputs:

- GHG reductions attributed to British Columbia's LCFS: The amount of emissions reduced as a result of the inclusion of the LCFS policy in a policy package relative to the emission reductions that occur without the LCFS.
- WTW GHG reductions: emissions must decline 80% by 2050 in both the personal transportation sector and the freight transportation sector (relative to 2007 levels) (Government of B.C., 2007).
- Quantity of fuel demanded by CIMS-LCFS and subsequently supplied in the fuel supply optimization model: measured in terms of energy content (i.e. gigajoules).

Chapter 3. Results

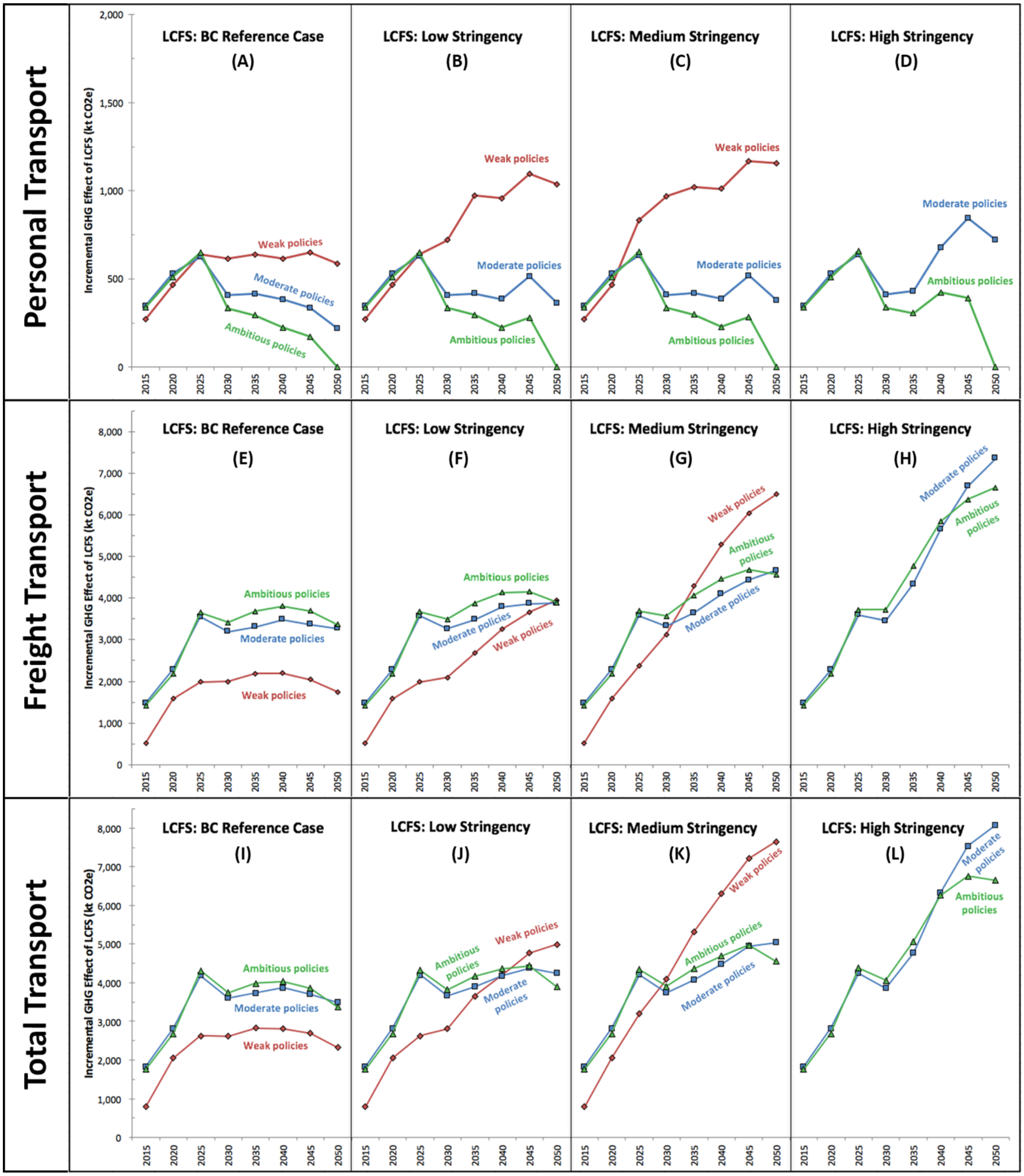
Below, I present the results of my modelling simulations in the context of my research objectives, focusing on WTW GHG emission reductions, vehicle market shares, and alternative fuel market shares. I simulate a series of policy scenarios focusing on the LCFS when accompanied with other transportation policies of various stringencies. CIMS-LCFS was able to successfully solve all policy scenarios – meaning that compliance with all policies was feasible given the various parameters and constraints – except for the High stringency LCFS accompanied with the Weak "non-LCFS" policy package. In this one case, the model failed to achieve the 2030 target of a 30% reduction in carbon intensity, largely due to the Weak policy scenario's inability to increase alternative vehicle uptake and fuel demand. I present and discuss my results for the personal and freight transport sectors separately due to differences in size, projected growth, and available vehicle technologies.

3.1. Objective 1: The effectiveness of the LCFS at reducing GHG emissions

My first research objective explores the GHG effectiveness of the LCFS when accompanied with other transportation policies of various stringencies – that is, what "additive" or incremental impact can be attributed to the LCFS. I determine the LCFS' effectiveness at reducing GHG emissions by analyzing the additional emission reductions that occur as a result of including the LCFS policy in the different policy package scenarios relative to the same policy package scenario without the LCFS. The goal is to identify the types of policy environments that make the LCFS complementary, transitional, and redundant, as I define them in Section 1.5.: i) I consider the LCFS to be complementary if it has a positive incremental effect on GHG emission reductions in every period of the simulation when included in a policy package scenario, ii) I classify the LCFS as transitional if it has a positive incremental effect on GHG emission reductions during the initial periods of the simulation before experiencing a decreasing incremental effect that ultimately declines to zero, and iii) I consider the LCFS redundant if it does not have a positive incremental effect on GHG emission reductions in any period of the simulation. Next, I explain a little more about how to interpret Figure 4. I then present my results for the entire transportation sector before discussing the two subsectors, personal and freight, in greater detail. I conclude this section by presenting the results of my sensitivity analysis on the effectiveness of the LCFS.

Figure 4 summarizes the incremental WTW GHG effectiveness of the LCFS at different stringencies for the personal, freight, and total transportation sectors. The LCFS's incremental GHG effectiveness for each "non-LCFS" policy package is illustrated by data points in each period of the simulation, with the area under the curves representing the total emissions abated from the inclusion of the LCFS. I depict results for a total of 11 model scenarios (12 minus the one scenario that did not solve). Note that the "total" row of figures is just the summation of additive impacts from the "personal" and "freight" figures above it. Across these scenarios, the LCFS is complementary in all scenarios for the freight sector (Figures 4E to FH), and the transport sector overall (Figures 4I to 4L), as indicated by an increasing or plateauing line over time. The LCFS is only transitional in a few scenarios for the personal transport sector, for example, in Figure 4C, the Medium stringency LCFS plays a transitional role as it reduces fewer and fewer emissions as the simulation progresses in the Moderate and Ambitious policy scenarios. In general, as the LCFS stringency increases, the incremental GHG effectiveness of the LCFS also increases across both sectors (all else held constant).

Figure 4. The incremental GHG effectiveness of the LCFS (kt CO_2e) when accompanied with other "Non-LCFS" policy packages (Weak, Moderate and Ambitious)



Note: The policy scenario containing a High stringency LCFS (Figure D, H, L) accompanied with Weak "non-LCFS" policies is not included in Figure 4 because the scenario was "infeasible" in that it failed to achieve the required LCFS reduction targets.

To illustrate how to interpret Figure 4, I use the example of the "BC Reference Case" LCFS that requires a 10% reduction in carbon intensity by 2020, with the 10% reduction target then being maintained out to

2050. Referring to Figure 4I, the “BC Reference Case” LCFS is complementary to the “non-LCFS” policies in the three policy packages – Weak, Moderate, and Ambitious. Looking more specifically at the Weak “non-LCFS” policy package in 2050, the inclusion of the “BC Reference Case” LCFS reduces total transport emissions by an additional 2,328 kt CO_2e (Figure 4I), with reductions of 586 kt CO_2e coming from personal transport (Figure 4A) and 1,742 kt CO_2e coming from freight transport (Figure 4E). In terms of the overall quantity of emission reductions needed to achieve the 2050 GHG target, the LCFS contributes 7% of the emission reductions required in the personal sector in 2050, 8% of the reductions required in the freight sector, and 7% of the overall reductions required in 2050 across the entire transportation sector. Note that the LCFS is an intensity standard and not an absolute standard; thus, achieving a 10% reduction in the carbon intensity of transportation fuels does not necessarily translate into absolute emission reductions of the same magnitude (i.e. the incremental impact of the LCFS). Recall from section 2.2. that the demand for travel – measured in VKT and TKT – increases each period based on an exogenous growth factor. Therefore, although carbon intensity is decreasing as a result of the LCFS, absolute emissions do not decrease by the same magnitude due in part to the increase in travel demand as the simulation progresses.

Within the entire (i.e. total) transportation sector (Figures 4I to 4L), the LCFS is complementary in that having a LCFS always results in additional emission reductions above the emission reductions that would have occurred without the LCFS (in each scenario, in each year simulated). In other words, the LCFS is never redundant in that the inclusion of the LCFS always results in additional emission reductions within a particular policy scenario. Further, in most cases, the “additive” effect of the LCFS at reducing GHG emissions increases as the simulation progresses from 2015 to 2050. For example, the inclusion of a High stringency LCFS with Moderate “non-LCFS” polices (Figure 4L) reduces total transport emissions by an additional 8,074 kt CO_2e (Figure 4L), with reductions of 721 kt CO_2e coming from personal transport (Figure 4D) and 7,353 kt CO_2e coming from freight transport (Figure 4H). In terms of the overall quantity of emission reductions needed to achieve the 2050 GHG target, with Moderate “non-LCFS” policies, a High stringency LCFS contributes 8% of the emission reductions required in the personal sector in 2050, 33% of the reductions required in the freight sector, and 26% of the overall reductions required in 2050 across the entire transportation sector.

In personal transport, the LCFS always has an additive impact across all scenarios, with the largest additive effect occurring in the presence of Weak “non-LCFS” policies (Figure 4A to 4C). In this scenario, the omission of the ZEV mandate and less stringent carbon tax (recall from Table 8) leads to relatively low ZEV uptake during the simulation; in turn, the LCFS does most of the “heavy lifting” in terms of emission reductions through the supply of ethanol blended into gasoline, with some E85 also being supplied. As an example, under the Medium LCFS scenario that requires a 35% reduction in carbon intensity in 2045 (Figure 4C), the LCFS reduces emissions by 1169 kt CO_2e when accompanied with Weak policies, 519 kt CO_2e with Moderate policies, and 284 kt CO_2e with Ambitious policies. In terms of overall quantity of emission reductions required to achieve the 2050 GHG target, the LCFS accompanied with the Weak policy package accounts for 14% of the emission reductions required, 6% with the Moderate policy package, and 3% with the Ambitious policy package.

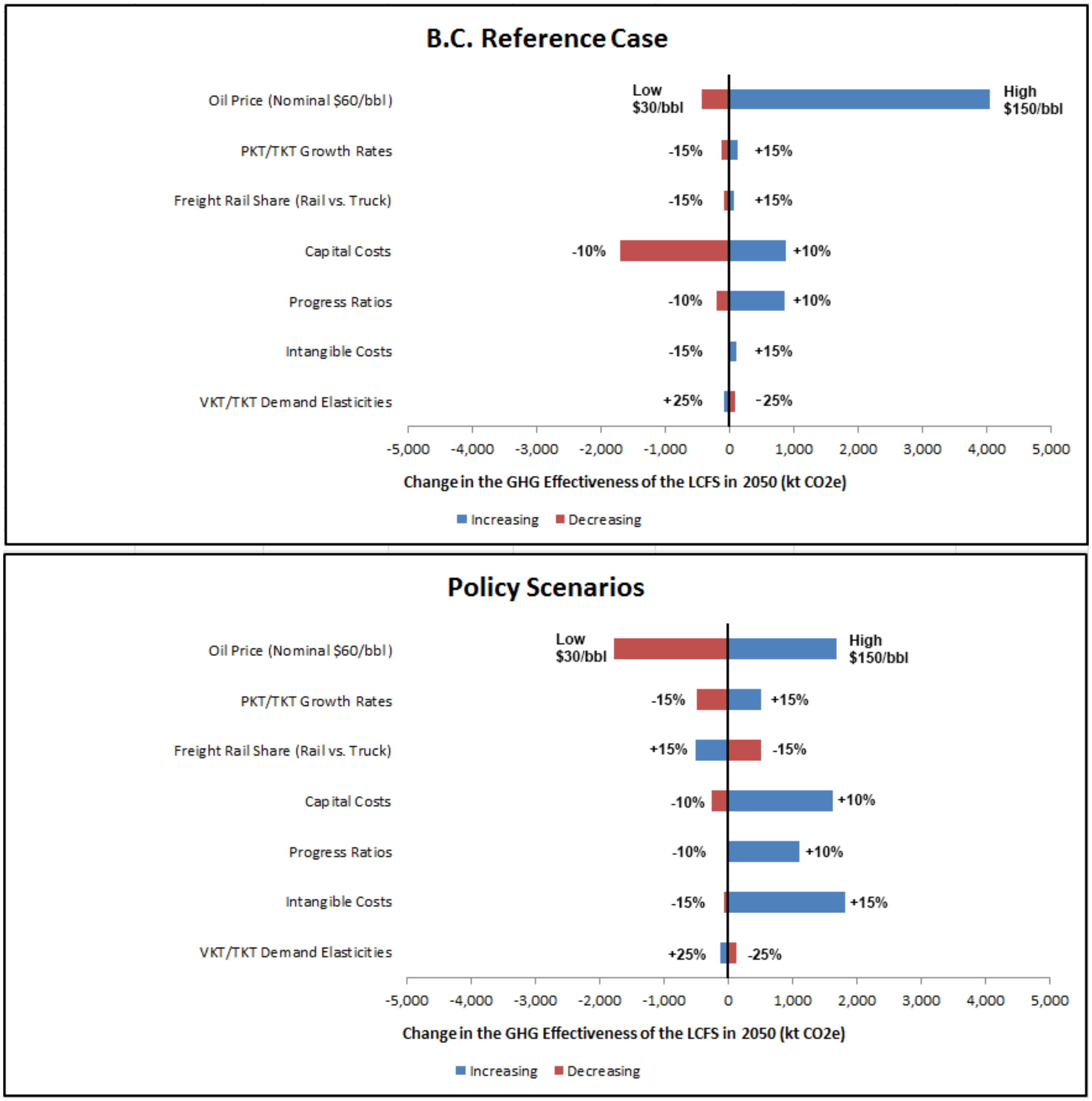
Further, the LCFS is transitional in four of the policy scenarios in the personal transportation sector, where the LCFS impact declines to zero by the end of the simulation period. This decline occurs when the LCFS is accompanied with the Ambitious "non-LCFS" policy package (for all stringencies of the LCFS; Figure 4A to 4D). The decreasing incremental GHG impact occurs because emission reductions resulting from the uptake of electric vehicles in the Moderate and Ambitious policy packages would occur regardless of the inclusion of the LCFS. Recall from Table 8 that the Ambitious policy package includes both a stringent ZEV mandate and a stringent carbon tax (rising to \$350/t CO_2e in 2050). In this scenario, the stringent ZEV mandate and carbon tax lead to a rapid uptake of battery electric vehicles (BEVs) in the personal sector; as the simulation progresses, LCFS reduction targets are then largely met by supplying electricity. Since the LCFS did not cause the uptake in electric vehicles, and electricity in British Columbia is already relatively low carbon, the GHG impact of the LCFS is relatively small compared to the same LCFS accompanied with the Weak "non-LCFS" polices. Additionally, the larger electric vehicle population leads to a decrease in the consumption of gasoline and diesel; consequently, there are lower volumes of blended renewable fuel supplied in those scenarios (see Figure 9 in section 3.3.).

In the freight sector, the LCFS is complementary in every period of the simulation across all policy scenarios (Figure 4E to 4H). Moreover, the additive impacts of the LCFS are proportionally larger than they are in the personal sector. In the more stringent LCFS scenarios – Low, Medium, and High stringency – the additive impacts of the LCFS increase as the simulation progresses out to 2050 for the Weak and Moderate "non-LCFS" policy scenarios (Figure 4F to 4H). However, when accompanied with Ambitious "non-LCFS" policies, the incremental impact of the LCFS eventually plateaus in 2045 before slightly decreasing in 2050. This decline in GHG reductions from the LCFS can be largely attributed to the electrification of light/medium freight trucks and freight rail. Similar to personal transport, the uptake in electric vehicles is predominately driven by other policies – ZEV mandate and carbon tax. The increased supply of electricity generates credits that contribute to LCFS compliance, but are not attributed to the effectiveness of the LCFS due to British Columbia's existing low carbon electricity generation capacity.

In contrast to the personal sector, the LCFS within the freight sector remains complementary as the "non-LCFS" policies become more stringent. This increasing additive GHG effect of the LCFS can be largely attributed to the more diverse vehicle composition under the various policy scenarios. In the presence of Weak "non-LCFS" policies, the freight sector's vehicle composition remains heavily skewed towards gasoline and diesel vehicles, with some hydrogen FCEVs in the heavy freight sector. LCFS reductions targets are then largely fulfilled by supplying low carbon hydrogen from electrolysis and waste capture, and by blending additional amounts of low carbon ethanol, biodiesel, and HDRD into gasoline and diesel. When accompanied with Moderate and Ambitious "non-LCFS" policies, the freight sector's vehicle composition consists mainly of hydrogen FCEVs for heavy freight trucks and electric vehicles for light/medium freight trucks and freight rail. As a result of the wide variety of alternative fuels demanded in the freight sector, the LCFS experiences an increasingly additive GHG impact across all "non-LCFS" scenarios by ensuring that those transport fuels that are not inherently low carbon (e.g. hydrogen, HDRD, biodiesel, LNG, etc.) are produced from low carbon sources.

To better understand the sensitivity of these results, I use single-value deterministic sensitivity analysis to explore how variations in seven key input parameters affect the resulting GHG impact of the LCFS. In circumstances where parameters are closely related, I vary multiple parameters jointly as this can produce a more practical measure of sensitivity (Kann & Weyant, 2000). Sensitivity analysis indicates that the amount of incremental emissions reduced from the LCFS is most sensitive to four parameters: i) the price of oil, ii) capital costs of vehicles, iii) intangible costs, and iv) vehicle and fuel progress ratios. For the capital costs of vehicles, I vary the purchase price of all non-gasoline and diesel vehicles due to the uncertainty in expected cost savings realized from economies of scale and learning by doing. Furthermore, I vary the progress ratios of the fuel technologies that do not yet have fully developed independent supply chains; that is, the fuel progress ratios for biodiesel, electricity, ethanol, hydrogen, natural gas (CNG and LNG), and HDRD. Figure 5 depicts the sensitivity of the GHG impact of the LCFS in 2050 for both the reference case and policy scenarios. For the policy scenarios, I take the most extreme change in LCFS effectiveness across all policy scenarios and combine them to form a single "policy scenario" diagram. I combine the sensitivity results for the policy scenarios into a single diagram because of the similarities in sensitivities across the different policy scenarios, which allows for a clearer, less cluttered visual communication of the results. Figure 5 illustrates the change in the GHG impact of the LCFS relative to its impact using nominal parameter values. Of the parameters tested, my model's results are relatively less sensitive to projected PKT/TKT growth rates, freight rail share, and VKT/TKT demand elasticities. In general, variation in the individual parameters produces an asymmetric change in the impact of the LCFS; the model is more sensitive to increases in the price of oil, vehicle costs, and progress ratios than to decreases.

Figure 5. Sensitivity analysis: Change in the GHG impact of the LCFS in 2050 (kt CO_2e)



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

My second research objective investigates the ability of British Columbia to meet its 2050 GHG target in the transportation sector, with different stringency levels of the LCFS and other policies. I investigate the same simulations of policy scenarios presented in the previous section, but now present this information according to the ability of each scenario to achieve British Columbia's 2050 GHG target for the transportation sector. As in Section 3.1 above, I first provide an explanation of how to interpret Figure 6 and then present the results for the entire transportation sector before discussing the two subsectors, personal and freight, in greater detail. I conclude this section by presenting the results of my sensitivity analysis on the ability of British Columbia to achieve its 2050 GHG target.

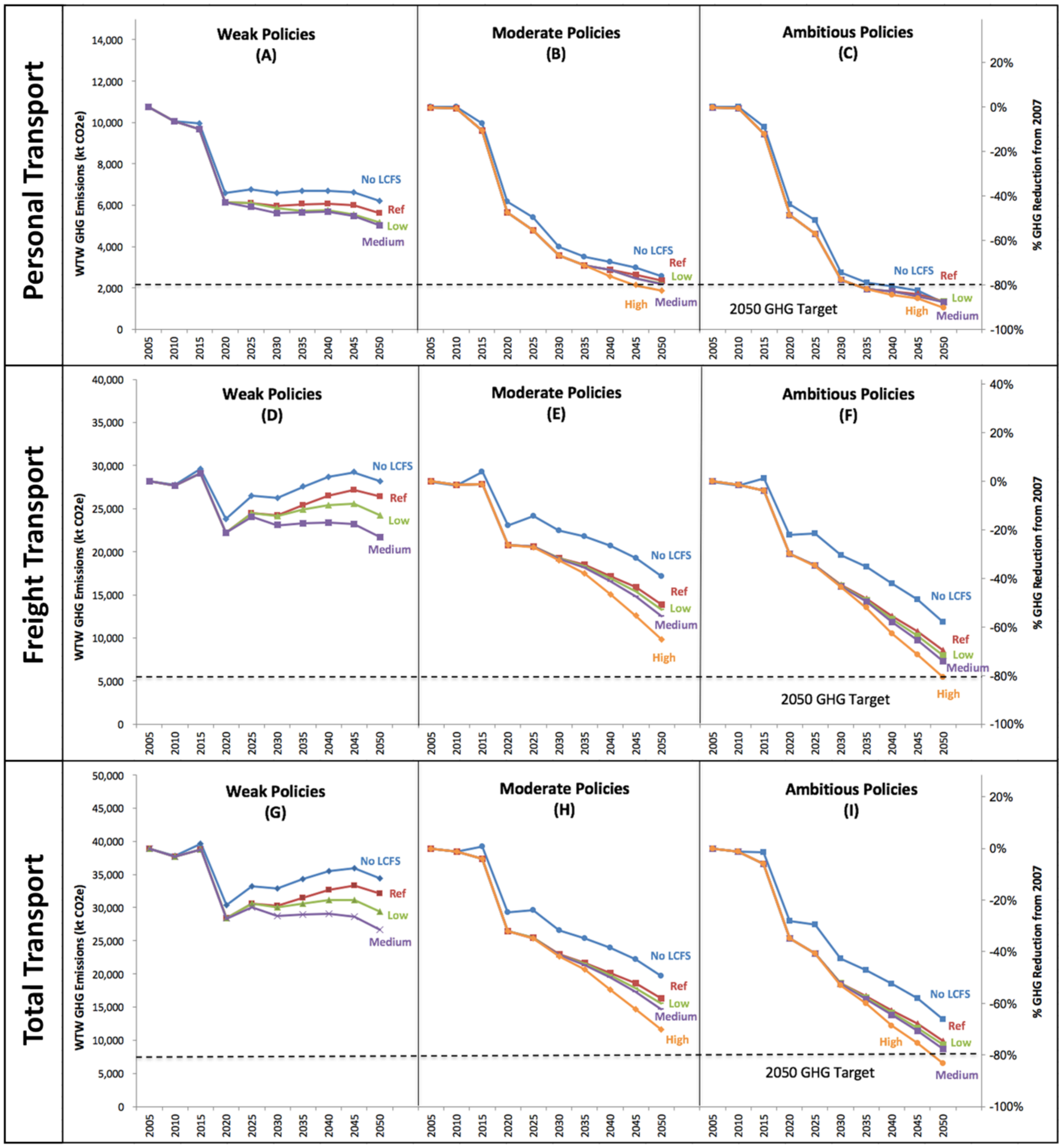
Figure 6 is similar to Figure 4 in that it presents my results for the different sectors – personal, freight, and total transport. I use the same policy scenarios, but organize the columns according to the stringency of the non-LCFS policies (Weak, Moderate and Ambitious), where for each figure, the different lines represent the four LCFS scenarios (No LCFS, BC Reference Case, Low, Medium, and High stringency). In Figure 6, WTW GHG emissions are represented on the primary y-axis (left-hand side of the chart) and the percentage reduction relative to 2007 levels is represented on the secondary y-axis (right-hand side of the chart). Recall that the 2050 GHG target requires an 80% reduction from 2007 levels by 2050, as indicated by the dotted line running horizontally across the charts.

To illustrate how to interpret Figure 6, I use the example of the reference case scenario, which is designed to mirror British Columbia's current policy environment with respect to the LCFS and other policies. Specifically, the "B.C. Reference Case" LCFS requires a 10% reduction in carbon intensity by 2020, with the 10% reduction target then being maintained out to 2050. The "B.C. Reference Case" LCFS is accompanied with Weak "non-LCFS" policies that include a carbon tax frozen at $30/tonne of CO_2e, vehicle GHG standards to 2025, and a ZEV purchase subsidy that runs until 2020. In this scenario, British Columbia's transportation sector achieves a modest 18% reduction in WTW GHG emissions relative to 2007 levels, where reductions are mainly due to the existing CAFE standards that level off in 2025 (Figure 6G). The 18% reduction is determined by looking at the last data point on the red "Ref" line in Figure 6G, following horizontally to the secondary y-axis shows that this scenario resulted in an 18% reduction relative to 2007 levels. Broken down into the two subsectors, the personal transportation sector achieves a 49% reduction relative to 2007 (Figure 6A), and the freight sector achieves a 6% reduction in WTW GHG emissions by 2050 (Figure 6D).

Across the entire transportation sector, British Columbia is only able to achieve its 2050 GHG target in the most stringent policy scenario: the High stringency LCFS accompanied with Ambitious "non-LCFS" policies, which leads to a reduction of 83% relative to 2007 levels. When accompanied with Weak "non-LCFS" policies (Figure 4G), the transport sector achieves modest reductions ranging from 12% (No LCFS) to 31% (Medium stringency LCFS). Recall from section 4 that the model's outputs for the High stringency LCFS accompanied with Weak "non-LCFS" policies are not shown in Figure 6 because the model failed to meet the High stringency LCFS scenario targets. Under the Moderate policy scenarios (Figure 4H), the transport sector achieves reductions in 2050 between 49% (No LCFS) to 70% (High stringency LCFS). Further, the transport sector gets close to achieving the 2050 GHG target in the

Ambitious policy scenarios, ranging from 66% (No LCFS) to 78% (Medium stringency LCFS), before actually achieving the target with the High stringency LCFS.

Figure 6. The 2050 GHG target: Absolute WTW GHG emissions (kt CO2e)



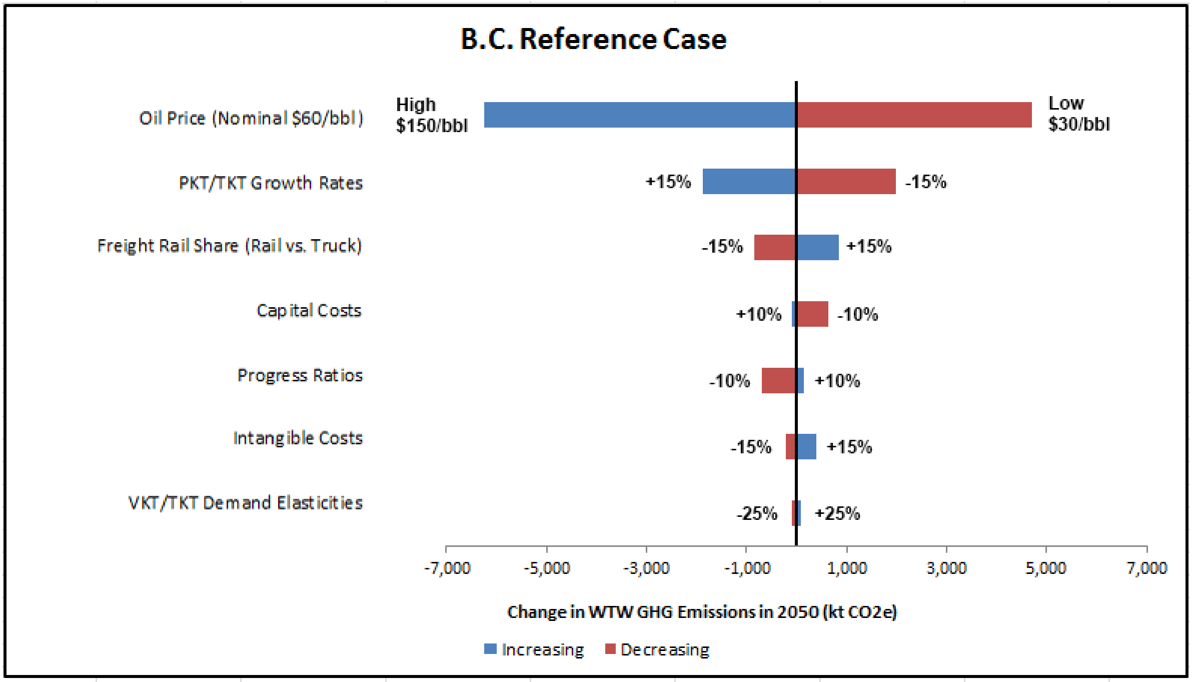
Note: The High stringency LCFS accompanied with Weak "non-LCFS" policies is not included in Figure 6 because the scenario was "infeasible" in that it failed to achieve the required LCFS reduction targets.

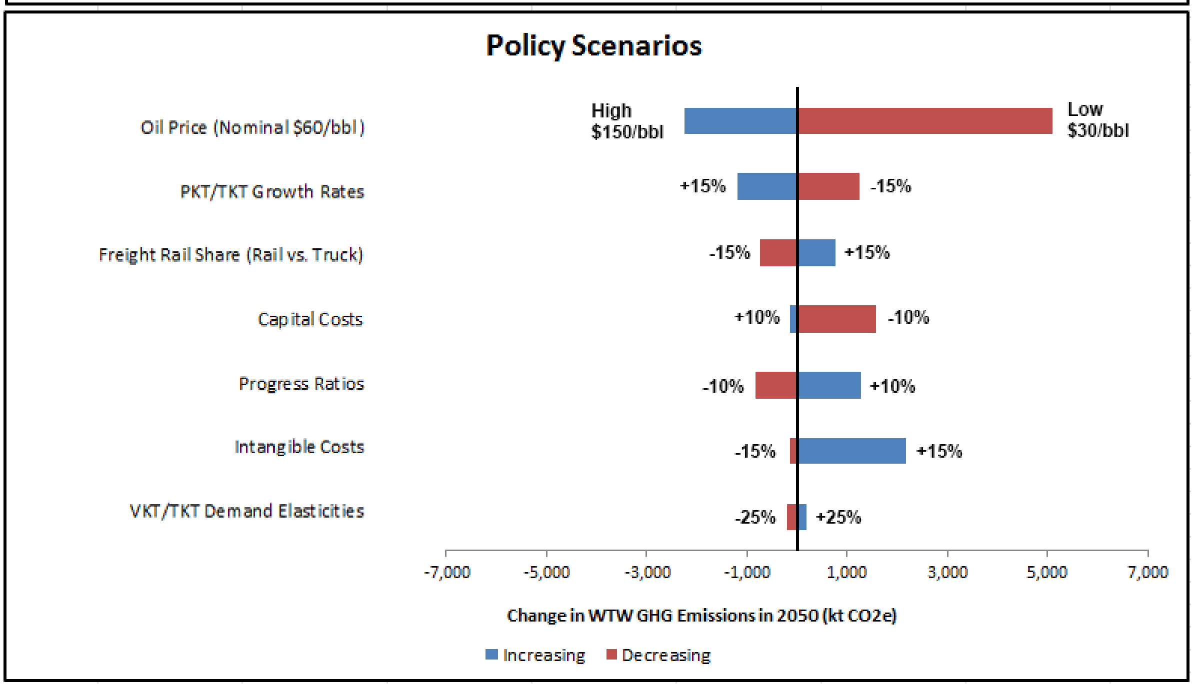
The personal transportation sector achieves or comes close to achieving British Columbia's 2050 GHG target in all LCFS scenarios when accompanied with Moderate and Ambitious "non-LCFS" policies. When accompanied with Moderate "non-LCFS" policies (Figure 4B), the personal sector achieves between 76% (No LCFS) to 79% (Medium stringency LCFS) before achieving the target with the High stringency LCFS (83% reduction). Further, British Columbia's personal transportation sector achieves the 2050 GHG target in all of the Ambitious "non-LCFS" policy scenarios (Figure 4C), with the highest reductions occurring with the High stringency LCFS – a 90% reduction. In contrast, when accompanied with Weak "non-LCFS" policies, the personal sector achieves relatively deep GHG reductions between 42% (No LCFS) and 53% (Medium stringency LCFS).

Similar to the entire (total) transportation sector, the freight transport sector is only able to achieve the 2050 GHG target in the most stringent policy scenario: the High stringency LCFS accompanied with Ambitious "non-LCFS" policies, leading to an 81% reduction relative to 2007 levels. When accompanied with Weak "non-LCFS" policies, the freight sector achieves modest reductions, with the largest occurring with the Medium LCFS – a 23% decrease in emissions. Moreover, with Moderate "non-LCFS" policies, the freight sector is unable to meet the 2050 GHG target, achieving reductions ranging from 39% (No LCFS) to 65% (High stringency LCFS). In the Ambitious policy scenarios, the freight sector gets close to achieving the 2050 GHG target with reductions ranging from 58% (No LCFS) to 74% (Medium stringency LCFS), eventually achieving the target with the High stringency LCFS (81% reduction).

Sensitivity analysis reveals that WTW GHG emissions in the transportation sector in 2050 are most sensitive to the price of oil ($/bbl). Figure 7 depicts the sensitivity of the quantity of emissions reduced in 2050 relative to the results when using nominal parameter values for both the reference case and policy scenarios. Recall that for the policy scenarios, I take the most extreme change in emission reductions across all policy scenarios and combine them to form a single "policy scenario" tornado diagram. Fluctuations in the price of oil affect the production costs of gasoline, diesel, and other alternative fuels; this in turn affects the end-use prices for the different transport fuels. For example, having a lower oil price makes gasoline and diesel vehicles more attractive compared to other alternative vehicle technologies, which leads to an increase in gasoline and diesel vehicle use that ultimately leads to an increase in WTW GHG emissions across all scenarios. In the policy scenarios, variation in the individual parameters produces an asymmetric change in the quantity of emissions reduced in 2050; the model is more sensitive to decreases in the price of oil and capital costs, and to increases in the intangible costs of vehicles and vehicle and fuel progress ratios.

Figure 7. Sensitivity analysis: Change in WTW GHG emissions in 2050 (kt CO2e)



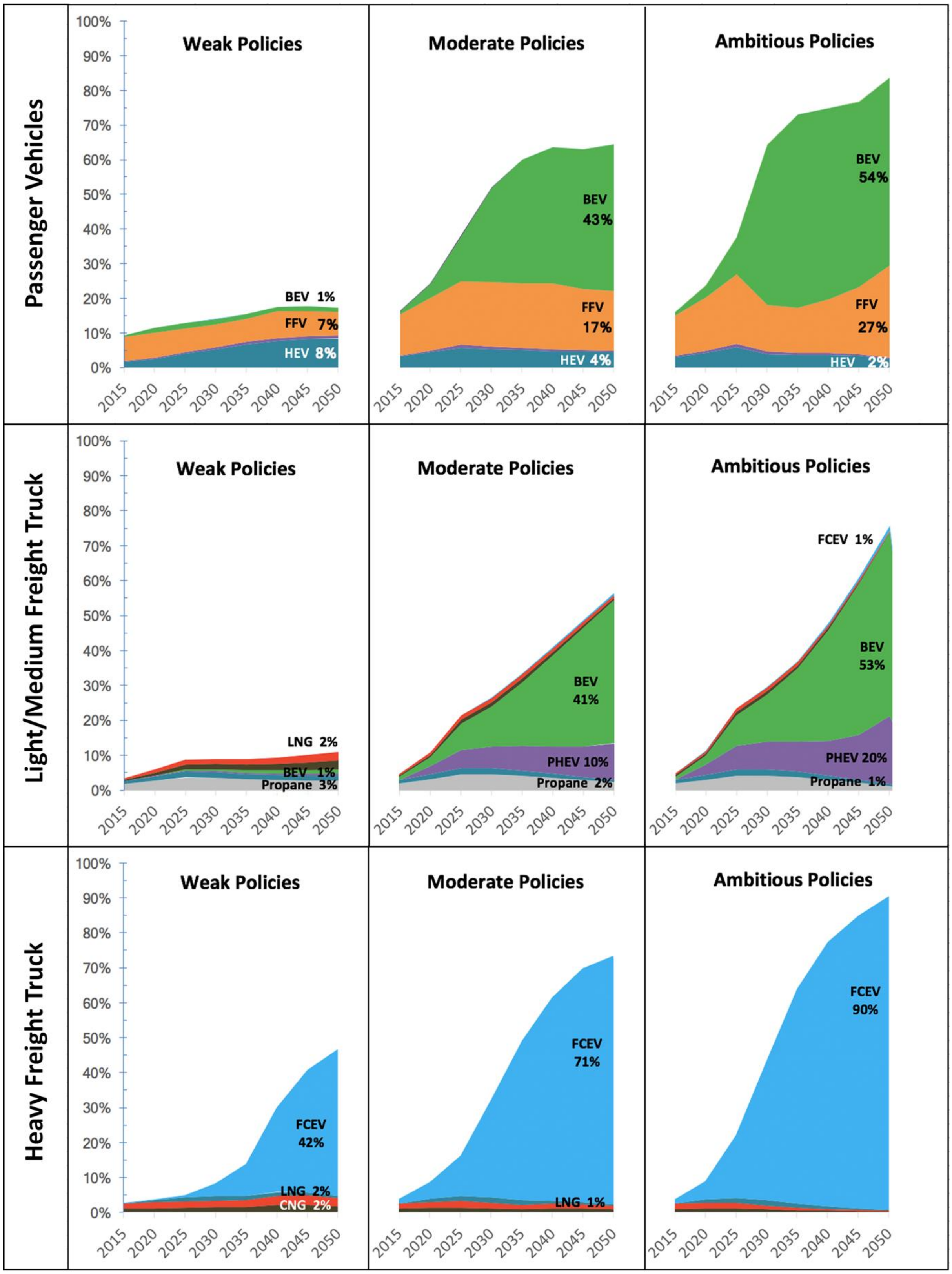


3.3. Vehicle technology and fuel market shares

To better explain the modeled effects of the various policy scenarios on vehicle adoption and fuel use, Figure 8 summarizes the alternative vehicle market shares in 2050 under the High stringency LCFS for three of the largest sectors in my model: passenger vehicles, light/medium freight trucks, and heavy freight trucks. Zero emission vehicle adoption is primarily driven by the ZEV mandate, and to a lesser extent the rising carbon tax. Battery electric vehicle (BEV) uptake increases significantly under the Moderate and Ambitious policy scenarios in both the passenger vehicle sector and the light/medium freight truck sector. In the passenger vehicle sector, the uptake of flex fuel vehicles (FFVs) is also noteworthy, rising from 7% in the Weak policy package to 17% and 27% in the Moderate and Ambitious policy packages respectively. Although the carbon tax raises the life cycle cost of FFVs, the magnitude of the increase is less than that of conventional gasoline vehicles. Recall from section 2.10. that the carbon tax is applied to each fuel based on its respective life cycle emissions in the Moderate and Ambitious policy scenarios. Therefore, the carbon tax incentivizes the use of low carbon, high-level ethanol blends as the stringency of the carbon tax increases. The ability to consume lower carbon E85 in FFVs lowers the vehicles' overall energy costs, which in turn lowers the associated life cycle cost of a FFV – making it more attractive to FFV drivers. Consequently, the relatively lower costing FFVs capture a larger portion of the market despite the rising carbon tax.

The heavy freight truck sector experiences a rapid uptake of FCEVs across all policy scenarios. Due to economies of scale and learning by doing, represented through the declining capital cost and declining fuel production cost functions, the cost of both hydrogen freight trucks and fuel declines during the simulations; consequently, long-haul hydrogen trucks begin to penetrate the heavy freight market in 2035, resulting in a 2050 market share of 42% in the Weak policy package. In the Moderate policy scenario, FCEV sales over-comply with the ZEV mandate that requires 65% of new vehicle sales to be FCEVs by achieving a 2050 total market share of 71%. Conventional diesel engines capable of running diesel, B20/R20, or R100 continue to play a meaningful role in long-haul freight comprising 27% of the total market share in 2050. In the Ambitious policy scenarios, approximately 90% of the heavy freight truck market is comprised of FCEVs by 2050, with conventional diesel engines making up the majority of the remaining market share at 9%.

Figure 8: Total alternative vehicle market shares for select sectors (%)



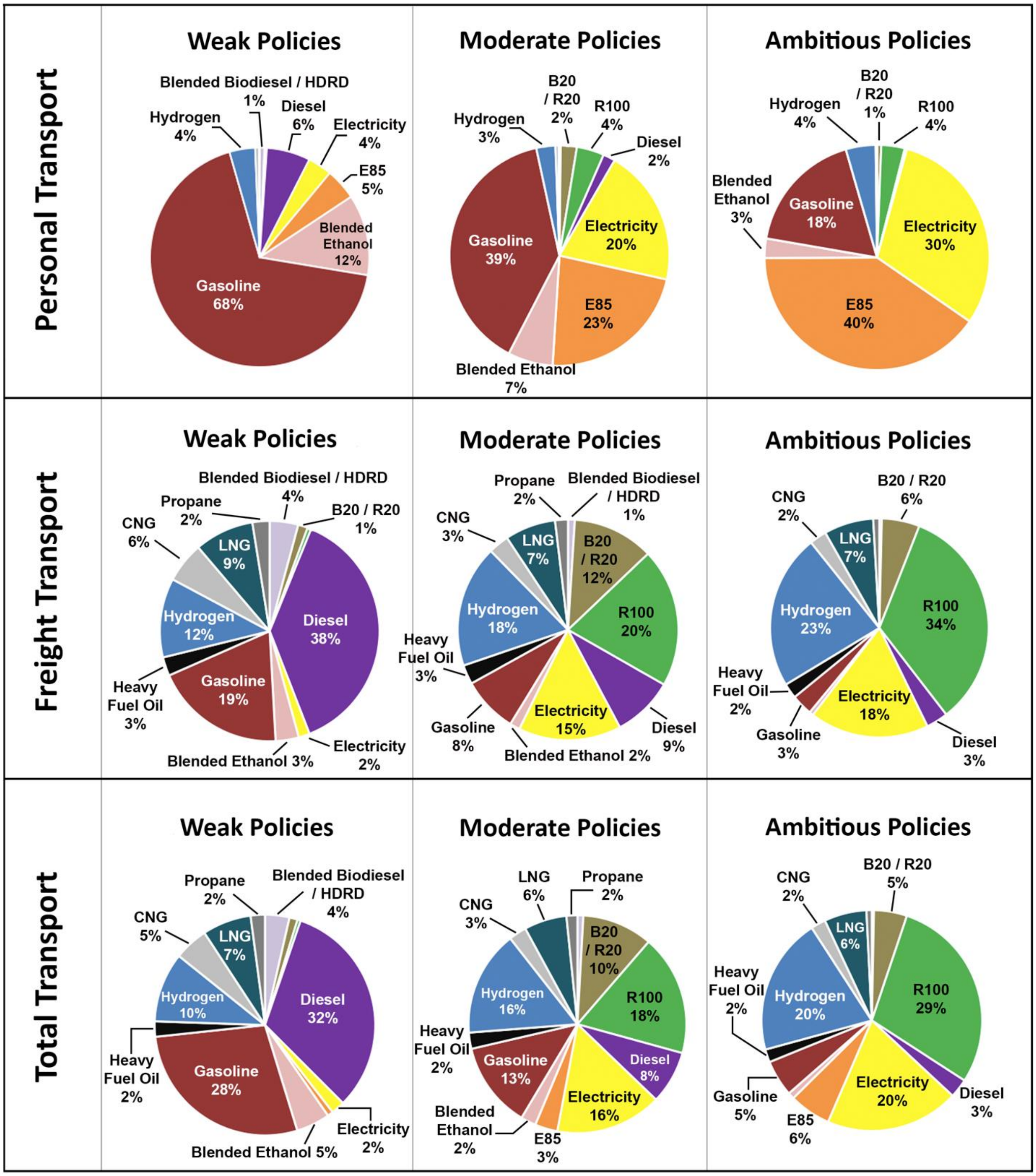
*The high stringency LCFS is used because LCFS stringency has very little effect on the CIMS-LCFS vehicle market shares.

Looking at fuel consumption, Figure 9 summarizes the percentage of total energy content captured by each fuel in 2050 for the three policy package scenarios under a Medium stringency LCFS. In the personal transport sector in 2050, under the Moderate and Ambitious policy scenarios, E85 comprises the largest percentage of alternative fuel consumed in terms of energy content, at 23% and 40% respectively. E85 is simulated to be largely produced from sugarcane ethanol in early periods of the simulation followed by cellulosic ethanol in later periods, where the switch is driven by both decreases in the costs of cellulosic ethanol and the need to supply lower carbon ethanol to comply with increasingly stringent LCFS reduction targets. Transportation-based electricity usage in 2050 also increases as the stringency of the policy package increases, from 4% in the Weak policy package to 20% in the Moderate scenario to 30% in the Ambitious policy package. Although BEVs capture a larger portion of the vehicle market in 2050 relative to FFVs, the lower drive-train efficiency of FFVs results in more E85 being consumed than electricity on an energy content basis. Furthermore, the gasoline market share in 2050 declines as the stringency of the policy package increases: from 68% in the Weak policy package to 39% in the Moderate policy package, and finally to 18% in the Ambitious policy package.

In the freight sector, electricity, hydrogen, and R100 comprise 75% of the transportation fuel consumed in 2050 in the Ambitious policy scenario. In contrast, gasoline and diesel consumption decreases to 6% of the total fuel demanded in 2050. As the simulation progresses, LCFS targets are met by supplying R100 derived from low carbon tallow- and yellow grease-based HDRD. These two feedstocks are preferred because they are modeled to be 67 to 83% less carbon intensive than petroleum diesel. Since the carbon tax is being applied to each fuel based on their respective life cycle GHG emissions, the increased supply of R100 from low carbon HDRD feedstocks reduces the tax levied on R100 relative to diesel, ultimately causing the price of R100 to fall below the price of diesel. Furthermore, the increase in hydrogen consumption is largely due to the ZEV mandate in the heavy freight truck sector while electricity consumption increases from the electrification of light/medium freight trucks and freight rail. In later periods, the hydrogen fuel supplied is produced via electrolysis and waste hydrogen capture. Lastly, LNG maintains a small portion of the fuel market – 7 to 9% – as a result of increased usage in the marine freight sector.

Across the entire (or total) transport sector, electricity, hydrogen and R100 comprise the majority of the fuel market under the Moderate and Ambitious policy scenarios in 2050 (69% of fuel demand). Although E85 plays a sizeable role in the personal transport sector in 2050 (up to 40%), it is not a major factor when considering fuel demand across the entire transport sector (up to 6%). Furthermore, gasoline and diesel consumption decreases dramatically as the “non-LCFS” policies become increasingly stringent, from 60% of the fuel market in the Weak policy package to 8% in the Ambitious policy package in 2050.

Figure 9. Market share percentage of fuels in 2050 for the policy scenarios (%; Medium LCFS)



Chapter 4. Discussion

The goal of my research is to explore the effectiveness of British Columbia's LCFS at reducing GHG emissions when accompanied with other transportation policies, and to assess the potential for British Columbia to achieve its 2050 GHG target through the implementation of a suite of transport policies. To accomplish my objectives, I simulate a series of policy scenarios using a dynamic hybrid energy-economy model (CIMS-LCFS) coupled with a fuel supply optimization model. To isolate the GHG impact of the LCFS, I run each policy scenario with and without the LCFS. I then analyze the difference in emission reductions that occur as a result of the inclusion of the LCFS and classify the policy as being either complementary (having additive mitigation impacts throughout the simulation period), transitional (having additive mitigation impacts in only the initial years of the simulation period, or redundant (having no additive mitigation impacts.

While previous LCFS literature has largely focused on California using either static accounting tools or a more dynamic energy-economy optimization model, CIMS-LCFS coupled with the fuel supply optimization model incorporates a number of endogenous factors including vehicle technology diffusion rates, declining capital costs and intangible costs, travel demand feedbacks, declining fuel production costs and prices, and alternative fuel availability at refuelling locations. Further, the CIMS-LCFS model includes endogenous functions that simulate consumer decisions regarding the mode of travel used in the passenger vehicle sector, and incorporates fuel switching for multi-fuel capable vehicles. Additionally, the model is the first to analyze the LCFS in the context of British Columbia while incorporating endogenous fuel supply decisions from a variety of different fuels and feedstocks. My modelling exercise is also unique in that I compare LCFS impacts across two distinct transport sectors: personal transportation and freight transportation.

The results of my study indicate that the LCFS is both effective (additive) at reducing GHG emissions and could play a strong role in achieving deep emission reduction targets across the entire transport sector. When accompanied with Ambitious "non-LCFS" policies, the inclusion of the LCFS in the transport sector was the difference between achieving (or almost achieving) British Columbia's 2050 GHG target and falling short of the target by a relatively large margin. While several previous studies have modelled the long-term effectiveness of the LCFS, comparison to my results is difficult because other studies did not attempt to isolate the additive effects of the LCFS, but instead explored the ability of a full suite of policies to achieve California's 2050 GHG target (McCollum et al., 2012, Yang et al., 2016). For example, McCollum et al. (2012) did not explicitly model the LCFS, but found that the resulting fuel supplied in their GHG reduction scenario would have achieved California's LCFS reduction targets. Moreover, both McCollum et al. (2012) and Yang et al. (2016) found that decarbonizing fuels in transportation played an important part of a "least-cost" pathway to achieving California's 2050 GHG target. Similarly, other studies focusing on the freight sector also found that the supply of low carbon alternative fuels will likely be needed to achieve deep emission reductions (Fulton & Miller, 2015).

Despite the overall potential importance of a LCFS in a suite of climate policies, its effects in the personal and freight sectors are very different. Specifically, the LCFS may not be as important for reducing GHG emissions in the personal transportation sector in the presence of other stringent policies. In the policy scenarios I construct, I find that the ZEV mandate and carbon tax are the most important drivers for significantly increasing ZEV uptake and reducing GHG emissions in the personal sector. Previous modelling literature that assessed the ability of a jurisdiction to meet its 2050 GHG target also found that a ZEV mandate played an important role in increasing ZEVs and alternative fuel use while also reducing GHG emissions (Yang et al., 2016). In the personal sector, my stringent policy simulations lead to a rapid uptake of battery electric vehicles (BEVs) and to a lesser extent flex fuel vehicles (FFVs) that can use E85. LCFS reduction targets are largely met by credits generated from the supply of electricity for these BEVs. Since electricity in British Columbia is already low carbon, the LCFS plays a transitional role in the personal sector. Meaning, the LCFS is effective at reducing emissions by ensuring that fuel consumed in the early and middle stages of the simulation are relatively low carbon until BEVs penetrate the market, at which time electricity becomes the major fuel for LCFS compliance. Although the supply of electricity assists in achieving LCFS reduction targets, I find that the LCFS experiences decreasing GHG effectiveness in the later stages of the simulation, and eventually the LCFS has no additive effect by 2050.

In contrast, my results indicate that the LCFS can play a much larger and more additive role in reducing GHG emissions within the freight sector, where fewer viable ZEV technologies exist for long-haul freight and marine. In general, I find that a stringent ZEV mandate and LCFS complement each other in reducing GHG emissions within freight – with both policies having substantial GHG reductions impacts when implemented together. In most cases, the LCFS has an even stronger additive impact when implemented with more stringent non-LCFS policies. The ZEV mandate drives hydrogen vehicle adoption in the heavy freight truck sector while the LCFS ensures that the hydrogen is produced from relatively low carbon sources – electrolysis and waste hydrogen capture. Similarly for marine freight, diesel and heavy fuel oil are replaced by LNG vessels, with the LCFS facilitating the supply of lower carbon renewable LNG. Further, the carbon tax and LCFS also complement each other in the Moderate and Ambitious scenarios, where the carbon tax is levied based on each fuel’s life cycle emissions. As the supply of low carbon biodiesel and HDRD increases under the LCFS, the carbon tax charge levied on those fuels decreases relative to petroleum diesel, making them more attractive for consumers with conventional diesel engines. Subsequently, the increase in demand for biodiesel and HDRD provides additional opportunities for LCFS compliance. While this variant of the carbon tax is important for facilitating fuel switching, the LCFS also plays an important role in ensuring that the renewable fuel blends supplied to the market originate from low carbon sources. Previous literature found similar results, where the supply of low carbon hydrogen and biofuels will likely be needed to achieve deep emission reductions within freight (Fulton & Miller, 2015). .

A point of comparison to previous literature is the achievement of LCFS reduction targets in the short-term, where my fuel supply optimization model is able to fulfill a 10% reduction in carbon intensity by 2020 in all policy scenarios – even with various technical and fuel demand constraints. Furthermore, my model found that carbon intensity reductions of between 10 to 27% were attainable in 2030 (in that the model was able to "solve" with the constraints in place). These results are similar to other studies focusing on California and the Pacific region of North America that estimated carbon intensity reductions between 5 to 15% by 2020 and 14 to 21% by 2030 (Farrell & Sperling, 2007a; ICF International, 2013; Malins et al., 2015).

Another point of comparison to previous literature is the resulting market shares of vehicle drivetrains and fuels under the 2050 target scenarios. My model simulates passenger vehicle ZEVs to account for 81% of vehicle kilometers travelled (VKT) within that sector by 2050. Yang et al. (2016) found similar results that estimated that passenger vehicle ZEVs would account for approximately 79% of vehicle miles travelled (VMT) in their 2050 GHG target scenarios. Further, biofuels account for a similar percentage of the fuel mix in 2050 across the two studies, with my model estimating biofuels at 37% of the fuel consumed compared to Yang et al. (2016) finding that biofuels accounted for 31 to 39% of the fuel mix in 2050. Gasoline and diesel consumption in Yang et al. (2016) was 82% below 2010 levels, compared to 92% below 2010 levels under my model's ambitious policy scenario with a high stringency LCFS.

However, my modeled outputs differ from these same studies in other areas. McCollum et al. (2012) and Yang et al. (2016) found that electricity and hydrogen accounted for 6 to 8% and 2 to 8% of the fuel consumed in 2050 respectively. In contrast, my model's results estimated electricity and hydrogen consumption in 2050 to be 19% and 20% respectively. The higher percentage of electricity and hydrogen usage in my model can likely be attributed to the inclusion of a stringent carbon tax (reaching $350/tonne in 2050) and a stringent ZEV mandate requiring 100% of new vehicle sales in the passenger vehicle and freight truck sectors to be ZEVs. In contrast, Yang et al. modelled a ZEV mandate that required 60% of new vehicle sales to be ZEVs in 2050 and did not include a carbon tax. Perhaps of equal importance, both McCollum et al. (2012) and Yang et al. (2016) modelled the 2050 GHG target across the entire California energy system, where significant GHG emission reductions occurred in other sectors besides transportation. In contrast, I model the 2050 GHG target exclusively within the transportation sector, where reductions cannot come from other sectors.

I conduct sensitivity analysis on seven key inputs to demonstrate that my results are most sensitive to assumptions regarding oil prices, and to a lesser extent, travel demand, capital and intangible costs, and the progress ratios of vehicles and fuels. Similar to Yang et al. (2016), the price of oil was the largest factor effecting cumulative emissions in 2050. This observation is not surprising because the price of oil affects both fuel production costs and end-use fuel prices in my model, with the magnitude of change in price for alternative fuels being informed from literature (Cazzola et al., 2013). Interestingly enough, increasing the capital costs, progress ratios, and intangible costs of all non-gasoline and diesel vehicles causes the LCFS to have a larger GHG impact in the policy scenarios. In contrast, decreasing the price of oil in the policy scenarios causes the LCFS to be less effective at reducing emissions.

4.1. Policy implications

In this section, I discuss the policy implications of my results in the context of British Columbia, although my results are likely applicable to other parts of Canada and the United States. As of the date of publication of this Research Project (April 2017), the Government of Canada is considering implementing a national clean fuel standard, potentially modelled after British Columbia's LCFS. Moreover, North American jurisdictions that already have a LCFS – British Columbia, California, and Oregon – are continuing to change and adapt their LCFS policies to an ever-changing transportation sector.

My results indicate that the LCFS can be a complement to other transport policies – zero emission vehicle (ZEV) mandate and a carbon tax – in the short-term within the passenger vehicle sector and in the short- and long-term within the freight sector. Recall that I define "complementarity" to mean that the LCFS has an additive effect on GHG emission reductions when included in a policy scenario, throughout the simulation period (from 2015 to 2050). Further, I find that the LCFS is not a redundant measure when accompanied with other transport policies. Recall that I define "redundancy" to mean that the LCFS does not have an additive effect on GHG emission reductions at any given point in time. Meaning, the inclusion of a LCFS never leads to additional emission reductions above those reductions that would have occurred without the LCFS. Moreover, in some scenarios for the freight sector, a given stringency of the LCFS becomes even more effective when the stringency of other policies increase. In general, I find that the ZEV mandate and carbon tax stimulate ZEV vehicle adoption as the vehicle stock turns over. In turn, the increased demand for alternative fuels provides additional compliance options for the LCFS. Further, the LCFS can complement the ZEV mandate and carbon tax by incentivizing the supply of low carbon alternative fuels, further reducing GHG emissions.

The LCFS may be a particularly important or useful policy design for decarbonizing the freight transportation sector, where few viable ZEV technologies exist for moving goods over long distances. Of the ZEV freight technologies that are currently commercially available, or close to it, almost all consume fuel that is not inherently low carbon. For example, the majority of hydrogen fuel in the United States is produced from natural gas reformation (U.S. DOE, n.d.), and renewable fuels – biodiesel and HDRD – can be more emission intensive than petroleum diesel when accounting for the fuel's life cycle emissions. My results suggest that the LCFS can reduce emissions in freight by incentivizing the supply of mid- and high-level low carbon renewable fuel blends for conventional diesel engines. In the long-term, whether the freight transport sector transitions to renewable fuel blends, LNG, or hydrogen, a stringent LCFS reduces emissions through the increased supply of lower carbon fuels. With freight activity expected to increase in the coming decades, my results suggest that a LCFS accompanied with other transport policies can substantially reduce GHG emissions within the freight sector. These results are consistent with previous research that found policies targeting the sale of ZEVs and the production of low carbon hydrogen and diesel-replacement biofuels will likely be needed to achieve significant emission reductions within freight (Fulton & Miller, 2015).

In contrast, the LCFS may not be as important in the passenger vehicle sector in the presence of other stringent policies. As my results indicate, under a complete vehicle composition transformation, the LCFS's effectiveness decreased to zero in 2050. However, the LCFS still played a transitional role in that the policy was effective at reducing GHG emissions as gasoline vehicles were retired for electric vehicles, especially through the supply of E85 in flex fuel vehicles (FFVs). It will likely take decades of strong policy to transform the passenger vehicle sector, and the LCFS can reduce emissions during that transition. Further, if the "non-LCFS" policies implemented in the passenger vehicle sector are not strong enough or are absent (e.g. carbon tax and ZEV mandate), then the incremental effects of the LCFS could become more important.

My results suggest that a transition to ZEVs consuming low carbon fuels is likely to play an important role in achieving deep emission reductions within the transport sector. Previous research focusing on decarbonizing transport, or the entire energy economy, found similar results (McCollum et al., 2012; Greene et al., 2014; Fulton & Miller, 2015; Lutsey et al., 2015; Robins et al., 2015; Yang et al., 2016). Furthermore, my results suggest that improvements in vehicle energy efficiency are also important to emission reductions. Although carbon pricing has the potential to drastically reduce emissions in transport, the stringency level that would be required would likely not be accepted by the public. Research on citizen acceptance of climate policy indicates that high levels of taxation are less politically acceptable compared to supply-focused regulations like the LCFS (Rhodes et al., 2014).

Focusing on the case study jurisdiction of the Canadian Province of British Columbia, the present suite of transportation policies (what I've called the "B.C. Reference Case") is not strong enough to induce the deep emission reductions required to achieve the province's 2050 GHG target. Moreover, my results indicate that even a relatively stringent LCFS on its own will not be enough to bring about the required emission reductions by 2050. My study suggests that obtaining an 80% reduction below 2007 levels in 2050 will still be a challenge in the presence of a full suite of ambitious policies. However, my study is limited in that I focus on the ability of the transport sector to achieve British Columbia's 2050 GHG target. In reality, significant emission reductions could occur in other sectors of the economy, such as the forestry and stationary combustion sectors. Nonetheless, with the transport sector emitting more GHG emissions than any other sector, stringent transportation policy will likely be needed to achieve the 2050 GHG target. The results of my study suggest that compulsory policy that drives ZEV uptake is the most important missing piece to reducing transport emissions in British Columbia. Implementing a ZEV-like policy to stimulate ZEV uptake will not only reduce emissions in transport, but it will also complement the existing LCFS and ensure its continued success.

With the Government of Canada's recent announcement to implement a national clean fuel standard, careful consideration should be given to policy design. First, the LCFS should be relatively stringent and long-term (e.g. out to 2050) to provide clear and consistent signals to fuel producers, fuel suppliers, and other transportation stakeholders. In particular, having a clear and consistent signal that the LCFS is a long-term initiative will help facilitate the necessary investments required to transform the transport sector, such as investments in emerging alternative fuels, fuelling infrastructure, and alternative vehicle technologies. Second, to achieve deep GHG emission reductions, a strong LCFS will likely need to be accompanied with other stringent policies – ZEV mandate, carbon tax, and vehicle GHG standards (i.e. fuel efficiency or CAFE-like standards). My study's results show that the LCFS is not only complementary to a suite of stringent "non-LCFS" transport policies, but that this full suite will likely be needed to achieve deep GHG emission reductions. Lastly, the LCFS and the Government of Canada's recently announced carbon pricing initiative should be designed to complement each other by incentivizing the supply of lower carbon fuels. In particular, the carbon tax regime should incorporate the LCFS' life cycle emission quantification system, where the carbon tax is levied based on each fuel's well-to-wheel (WTW) GHG emissions. Levying the carbon tax based on WTW GHG emissions would not only provide an incentive for consumers to purchase lower carbon fuels (through reduced end-use fuel prices), but it would also help provide additional compliance pathways for the LCFS through the supply of those lower carbon fuels, particularly mid- and high-level renewable fuel blends (e.g. B20/R20, R100, and E85).

4.2. Limitations and future research

The results of my study are highly dependent on the assumptions made regarding the technological advancement of alternative vehicles and fuels out to 2050. Key input data, such as fuel production costs, progress ratios, and vehicle fuel efficiencies, are estimated based on previous research; fuel carbon intensities are informed from data from either British Columbia's LCFS or using the GHGenius life cycle model. However, there is a large degree of uncertainty surrounding the actual path of technological development from now till 2050. Some promising vehicle and fuel technologies could fail while other new technologies could emerge. In regards to the LCFS, future research could look to incorporate some of the more encouraging fuel pathways that are just beginning to emerge and achieve commercialization. For example, there are companies nearing commercialization of renewable fuel oil (RFO) made from forest residues or other non-edible biomass that can used in co-processing at petroleum refineries (CPPI, 2016; Kotrba, 2016). With the ability to blend into gasoline and diesel at concentrations exceeding 50%, renewable fuel oil could reduce emissions by approximately 70% relative to petroleum gasoline and diesel (Kotrba, 2016).

My modelling exercise has several limitations stemming from model design and assumptions that ultimately affect the resulting output:

- The CIMS-LCFS model uses a static exogenous schedule based on historical data for allocating the percentage of freight goods that are moved by either rail or truck. Consequently, my model does not account for shifts across freight travel modes as a result of changes in costs, preferences, or policy. Existing freight mode choice research suggests that there are a number of factors that play a role in the decision to move goods by rail or truck: transport capacity, economies of scale and scope, financial costs, security concerns, environmental and energy concerns, safety, reliability, and responsiveness (Kullman, 1973; Oum, 1979; Cunningham, 1982; Cullinane & Toy, 2000; Norojono & Young, 2003; Meixell & Norbis, 2008). Future research could add endogenous freight mode decisions using capital costs and intangible costs for rail and truck competition. The complex nature of freight mode choice, and its potential impact on my study's results, made it an ideal candidate for sensitivity analysis.
- The uptake of hydrogen heavy-duty freight trucks in my Reference scenario is overly optimistic, where FCEVs comprise 42% of the heavy-duty freight truck market by 2050. The rapid uptake of FCEVs can be attributed to both decreases in the capital costs of the vehicles and decreases in the production costs of hydrogen fuel. The increased cumulative production of hydrogen technology in my model leads to reduced costs from economies of scale and learning by doing. While the hydrogen adoption rate for heavy freight trucks in the Reference case is optimistic, if anything, this leads to overly optimistic GHG reductions in 2050 in that scenario, due to hydrogen vehicles having a relatively high energy efficiency ratio (EER). In contrast, this is not an issue in the Moderate and Ambitious scenarios, where the stringent ZEV mandate drives hydrogen vehicle adoption for heavy freight trucks well above that of the Reference scenario.
- While my model incorporates endogenous price effects for emerging fuel technologies based on economies of scale and learning by doing, the model lacks endogenous feedbacks to fuel prices

based on changes in demand, particularly for gasoline and diesel. In CIMS-LCFS, gasoline and diesel follow an exogenous price schedule based on the National Energy Board's *Canada Energy Futures 2016* forecasts to 2040. Although gasoline and diesel prices can increase as a result of policy (e.g. carbon tax), they do not adjust to changes in demand. For example, in the Ambitious policy scenarios, gasoline and diesel comprise only ~8% of total fuel demand by 2050, on an energy content basis. The drastic decrease in petroleum fuel demand in this scenario would likely have a downward price effect on gasoline and diesel, where prices for those fuels would decrease. Similarly, prices of alternative fuels in higher demand – electricity, hydrogen, and R100 – would likely increase. It is unclear exactly how this would affect the GHG impact of the LCFS and the achievement of British Columbia's 2050 GHG target. However, sensitivity analysis indicates that the price of oil does have a relatively large effect on my model's results; therefore, it is fair to assume that incorporating endogenous price effects based on changes to the demand for fuels would have a measurable impact on my results.

- The fuel supply optimization model does not necessarily represent the collective behavior of individual fuel suppliers, but instead assumes a single large decision maker that makes rational fuel supply decisions across the entire transportation sector. The results of the fuel supply optimization model are the lowest cost outcomes given perfect information. In reality, these outcomes may not be the same as the cumulative impact of individual fuel supplier decisions. The results of the modelling exercise are not meant to be a forecast of what will occur under certain conditions, but rather an estimate of the fuel supplied and resulting GHG emissions given specified conditions and assumptions about the future composition of the transportation sector.
- Fuel supply decisions within the optimization model could be further improved by incorporating comprehensive cost curves for the various alternative transportation fuels. Due to a lack of available data for certain emerging fuels, I use simplified two-step cost curves to represent the limited availability of emerging alternative fuels. A more complete method for representing fuel supply decisions in a constrained world would be to develop and incorporate cost curves for each fuel and feedstock.
- Accounting for the sensitivity of the input assumptions to the model's results is limited by the use of single-deterministic sensitivity analysis. As a consequence of my interconnected model's structure, I was unable to use a more comprehensive method for conducting sensitivity analysis. The use of Monte Carlo analysis to run hundreds of iterations while varying the most critical parameters would improve the robustness of the model's results, better identify the most sensitive assumptions (parameters), and provide probability metrics for achieving British Columbia's 2050 GHG target under the various policy scenarios.
- When assessing the potential to achieve British Columbia's 2050 GHG target, I measure GHG emission reductions on a well-to-wheel (WTW) or life cycle basis. In reality, some of the GHG

emission reductions realized from consuming alternative fuels may occur outside of British Columbia, and thus not count towards the 2050 GHG target. To date, the majority of alternative fuel supplied to British Columbia under the LCFS has been produced at facilities located in other jurisdictions (B.C. MEM, 2016a). Therefore, some of the reductions in GHG emissions from improvements in fuel production processes and other upstream activities would not be applicable to British Columbia's 2050 GHG target.

- My model failed to achieve compliance with the High stringency LCFS when accompanied with Weak "non-LCFS" policies. Meaning that compliance with the High stringency LCFS was not feasible given the various parameters and constraints in the model under this policy scenario. To improve my modelling exercise, I could incorporate a "backstop fuel technology" into the fuel supply optimization model. "Backstop technologies" have been used in many energy-economy models and are generally known technologies that are not yet commercially available (Löschel, 2002). Further, a "backstop technology" is usually assumed to be available in unlimited supply at a constant, relatively high cost (Löschel, 2002). Incorporating a high cost "backstop fuel technology" would allow my model to solve for (i.e. achieve compliance with) even the most stringent LCFS scenario by supplying the "backstop fuel" as a last resort. One example of a "backstop fuel technology" that could be incorporated into my fuel supply optimization model is the co-processing of renewable fuel oil (RFO) at petroleum refineries. RFO is a stable, concentrated biocrude that can be produced from a variety of feedstocks, such as forest residues or waste from pulp mills (CPPI, 2016; Kotrba, 2016). Further, RFO is compatible with existing refinery technology and can be blended into petroleum fuels at relatively high concentrations (Kotrba, 2016).

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Appendix.

Table A.1. Progress ratios for transportation fuels

Fuel	Fuel Source	Progress Ratios
Biodiesel	Corn	0.97
	All other feedstocks	0.95
Electricity		0.90
Ethanol	Wheat & Corn	0.95
	Sugarcane	0.82
	Cellulosic	0.98
Hydrogen	Natural Gas Reformation	0.89
	Electrolysis & Waste Hydrogen Capture	0.82
Natural Gas	Fossil-based CNG & LNG	0.90
	Renewable CNG & LNG	0.95
HDRD	All feedstocks	0.95

Sources: Greaker et al., 2008; Schoots et al., 2008; de Wit et al., 2009; Chen et al., 2012

Table A.2. Zero emission vehicle (ZEV) mandate: ZEV technologies per sector

Vehicle technology	Passenger Vehicles	Light Freight Trucks	Heavy Freight Trucks
Flex Fuel Vehicles (FFVs)	▲		
Plug-in Hybrid Electric Vehicles (PHEV)	▲	▲	
Battery Electric Vehicles (BEV)	▲	▲	
Hydrogen Fuel Cell Electric Vehicles (FCEV)	▲	▲	▲