How to slash GHG emissions in the freight sector? Policy insights from a technology adoption model of Canada

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Abstract

The movement of goods through freight transportation accounts for approximately 6% of total Greenhouse Gas (GHG) emissions worldwide and 10% of Canada's emissions, yet the freight sector is rarely targeted by GHG abatement research and policy. To address this gap, I use a technology adoption model (CIMS-Freight) to explore the effectiveness of policies in achieving GHG reductions in land freight (trucking and rail), and to determine scenarios that achieve Canada's ambitious GHG reduction targets (i.e. 80% by 2050 relative to 2005 levels). To account for uncertainty in model parameters, I incorporate a Monte Carlo Analysis in which I run 1000 iterations of each simulation. My modeling results indicate that current policies (i.e. fuel efficiency standards as well as the federally proposed carbon price and low-carbon fuel standard) will not achieve 2030 and 2050 GHG reduction targets – where freight emissions will continue to rise, albeit at a lower rate than a "no policy" scenario. I also simulate the effectiveness of several individual policies: fuel efficiency standards, a carbon tax, low-carbon fuel standard (LCFS), a zero-emissions vehicle (ZEV) mandate for truck and purchase subsidy. Even at their most stringent levels, no individual policy has a high probability (at least 67% of Monte Carlo iterations) of achieving 2030 or 2050 GHG reduction targets. Finally, I find that several policy combinations can have a high probability of achieving 2050 goals, in particular a stringent ZEV mandate for trucks complemented by a stringent LCFS. While other effective policies and policy combinations are possible, it is clear that Canada's present and proposed policies are not nearly stringent enough to reach its ambitious emissions reductions targets.

Keywords: freight transport; trucking; climate policy; zero emission vehicle; zero emission vehicle mandate; low carbon fuel standard

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Chapter 1. Introduction

Globally, the transportation sector is responsible for approximately 14% of global greenhouse gas (GHG) emissions with freight transportation (goods movement by truck, rail, marine and air) alone producing approximately 6% of total emissions (Seo et al., 2016; Moultak et al., 2017). In Canada, freight emissions account for approximately 10% of the country’s emissions, and freight emissions are projected to surpass passenger vehicle emissions around 2030 to become the largest source of emissions in the transportation sector (ECCC, 2017). The Canadian government committed to reduce GHG emissions by 30% by 2030 and 80% by 2050 relative to 2005 levels (ECCC, 2017). However, freight emissions represent a particular challenge for Canada and countries around the world in achieving climate goals.

Trucks are the biggest source of freight GHG emissions and are responsible for approximately 87% of freight GHG emissions in Canada. Rail is responsible for approximately 7% of emissions, while marine and air combined are responsible for approximately 6% of emissions (ECCC, 2017). Freight demand by all modes is anticipated to grow, and freight movement by trucks in particular is predicted to increase more than twice as quickly as rail, air and marine in the next decade (ECCC, 2017). This increased demand for trucking is a result of an increase in inter-city, inter province and cross-border trade, demand for manufactured goods, and increased consumer expectations for goods to be transported quickly and for door-to-door service (Plumptre et al., 2017).

To date, the freight sector has been relatively ignored by policy makers (Plumptre et al., 2017, Mccollum et al., 2009), and without effective policies freight emissions will continue to increase (Plumptre et al., 2017; ECCC, 2017). A clear path towards deep decarbonization of freight transportation has been elusive (Moultak et al., 2017). Currently, there are a number of barriers to the widespread uptake of low carbon freight technologies, including limited commercial availability and economies of scale for low-carbon freight technologies; a lack of refueling infrastructure for potential low carbon freight fuels; and the heavy cargo weight, large size and long-distance travel requirements of freight vehicles.

1.1. Technology background

There are a wide variety of freight technologies on the market for both trucks and rail, each with their own characteristics. Trucking is further subdivided in to several classes with differing characteristics. In addition to conventional freight technologies, there are a number of technologies and fuels available that may help reduce freight emissions. Emissions reductions may be achieved through the use of technologies that increase the fuel efficiency of existing freight vehicles or by using less carbon intensive fossil fuels - such as natural gas or biofuels - or zero-tailpipe emission fuels, such as electricity and hydrogen. The market readiness of these technologies varies, with some commercially available and others still in development. In this section I review different freight classes, emissions-reducing technologies and fuel options for freight, and barriers to the adoption of these technologies and fuels.

There are several modes of freight whose usage and travel characteristics differ. For trucks, Transport Canada assigns freight trucks a Class between 2B and 8 based on their respective weight (Transport Canada, 2017). Based on class, freight trucks are sorted into three categories: light-duty, medium-duty and heavy-duty trucks (hereby referred to as light trucks, medium trucks and heavy trucks) (Transport Canada, 2017). Light trucks range from Class 2b to 3, medium trucks range from Class 4 to 6, and heavy trucks consist of Class 7 & 8. Currently in Canada, approximately 94% of medium and heavy trucks and locomotives use diesel instead of gasoline, because its higher energy density facilitates the movements of heavier loads (ECCC, 2017). Light trucks use a combination of diesel and gasoline depending on the class. Research suggests that achieving long term deep decarbonization in freight will likely require the adoption of zero-tail pipe emission vehicles (hereby referred to as ZEVs) (Moultak et al., 2017; Fulton et al., 2015; den Boer et al, 2013) and/or low carbon biofuels (Börjesson et al., 2015). However, the adoption of fuel efficiency technologies (Delgado et al., 2016) and technologies that use natural gas (Delgado et al., 2015) could also play a role in reducing freight GHG emissions, especially in the short-term with limited availability of ZEVs and low carbon fuels (Fulton et al., 2015).

Several fuel efficiency technologies are currently available that can be added to conventional diesel technologies for an incremental cost. In the 2030–2040 timeframe, researchers haves estimated that advanced fuel efficiency technologies will offer fuel efficiency improvements in the range of 30%-36% for light/medium trucks, 40%-52% for heavy tucks and 30%-40% for rail (Delgado et al., 2016). The commercial availability, incremental efficiency improvements and costs vary across technologies. Some fuel efficiency technologies, such as lower rolling resistance tires and improved aerodynamics, are readily available for relatively low incremental costs, but have modest fuel efficiency improvements (less than 5%) when adopted individually (US EIA, 2016). Other technologies, such as a hybrid system (electric motor powered by regenerate braking) and auxiliary power unit (a device that provides energy for functions other than propulsion), could result in more substantial efficiency improvements (10 to 30%), but these technologies are more expensive, and availability is limited (Delgado et al., 2016; Roeth et al., 2013). Additionally, a number of barriers exist for adoption of fuel efficiency technologies, including limited commercial availability of these technologies, lack of credible information to freight suppliers about the benefits from the adoption of these technologies, and uncertainty about the length of time required for fuel savings to pay back the investment in equipment (Roeth et al., 2013).

Freight technologies that use compressed natural gas (CNG) and liquified natural gas (LNG) are commercially available, but to date have experienced limited market penetration (less than 1% in North America) (Fulton et al., 2015). Research suggests that natural gas trucks could emit fewer well-to-wheel (WTW) GHG emissions (13%-34%) than conventional diesel trucks (Lajevardi et al., 2018; Shahraeeni et al., 2015). Barriers preventing the widespread adoption of natural gas vehicles include lack of refueling infrastructure, slightly higher vehicle costs, limited availability for purchase, and freight suppliers' lack of familiarity with these technologies (Fulton et al., 2015; Moultak et al., 2017).

A number of biofuels are available that could be used in place of diesel and gasoline. Specifically, biodiesel and hydrogenation-derived renewable diesel (HDRD) can be used in place of diesel and ethanol in place of gasoline. There are tail-pipe emissions associated with the burning of biofuels, but they are considered to be carbon neutral as carbon from tail-pipe emissions was absorbed from the atmosphere during production through photosynthesis in plants (Carbon Neutral Earth, 2018). However, there are upstream emissions associated with the growing and conversion practices involved in biofuel production (Fulton et al., 2015). There are a variety of feedstocks with different carbon intensities that could be used to produce biofuels, including corn, soy, and canola (Lepitzki et al., 2018). Upstream emissions would need to be addressed to achieve reduction goals from their adoption. Currently in Canada, diesel contains an average of 2% biodiesel and gasoline contains average of 5% ethanol (varies across provinces), but to run high blends of ethanol and biodiesel will require engine modifications (beyond 20 % biodiesel and 15% ethanol) (Iowa Renewable Fuels Association, 2019; National Biodiesel Board,2016). On the other hand, HDRD is a biofuel that does not require engine modification to run a high blend in trucks or locomotives (Miller, 2012; NRC, 2013). Barriers that have been identified for the widespread use of biofuels include the lack of fuel availability, higher fuel price, lack of vehicles capable of running high blends, and freight suppliers' lack of familiarity with high blends (Natural Resource Canada, 2018).

Trucks and locomotives that use electricity can be fueled via overhead catenary wires or batteries (Moultak et al., 2017; den Boer et al., 2013). Research suggests that these technologies can dramatically reduce GHG emissions compared to conventional diesel technologies, where the level of reduction will depend on the upstream emissions from the production of electricity (Moultak et al., 2017; Fulton et al., 2015; den Boer et al., 2013). Overhead catenary wires require the development of an infrastructure network before vehicle deployment (Moultak et al., 2017; den Boer et al., 2013). For rail, overhead catenary wires can be added to rail infrastructure. Unlike rail, trucks have more flexibility in travel routes as they are not restricted to travel along rail lines. As a result, widespread adoption of overhead catenary wires would require massive infrastructure development along all highways and roads. As a result, this technology may be best suited for drayage trucks that operate over shorter distances around ports and selected routes with high freight use (Moultak et al., 2017; den Boer et al., 2013). Admittedly, it is unclear if such infrastructure needs are necessarily greater for catenary trucks than for other alternative fuel pathways, such as hydrogen. While it is possible for trucks powered by overhead catenary wires to play a role in deep decarbonization of the freight sector, I do not include them in my analysis at the national level. Battery electric trucks for all classes are available or under development. Currently, battery electric trucks face substantial barriers to adoption, including limited electric range, high vehicle costs, and long charging times (Moultak et al., 2017; Fulton et al., 2015). Furthermore, battery electric heavy trucks face greater barriers than battery electric light/medium trucks due to the larger loads and longer distances travelled (Moultak et al., 2017).

Several freight vehicle technologies are under development that use hydrogen. Hydrogen technologies can dramatically reduce freight GHG emissions, but the effectiveness of these technologies in reducing emissions will depend on the production source of hydrogen. For example, most of hydrogen in North America is produced from natural gas reformation, which is carbon intensive (US DOE, N.D.). For my research, I limit my consideration of hydrogen to fuel cell technologies, which converts energy from hydrogen fuel into electricity through an electrochemical reaction with oxygen. However, there are other methods of producing hydrogen. Additionally, hydrogen fuel can also be blended with diesel and used in a combustion engine (Hydra, 2017). For hydrogen fuel cell freight vehicles, lack of refuelling infrastructure, limited commercial availability, hydrogen fuel costs, and vehicle costs have been identified as the prevailing barriers to widespread adoption (Moultak et al., 2017; Fulton et al., 2015).

1.2. Freight Policy Options

A number of policy options are available at the national or provincial level that could help reduce freight GHG emissions. Several researchers have identified four mitigation pathways that policies can target to address freight GHG emissions: improve vehicle technologies, reduce GHGs associated with fuels, reduce vehicle travel and increase modal share of less emission intensive modes (i.e. rail as opposed to heavy trucks, because rail is approximately seven times more efficient) (Plumptre et al., 2017; Nealer et al., 2012; Natural Resource Canada, 2012). Current trends indicate that Canada is experiencing a modal shift from rail to trucking (ECCC, 2017; Natural Resource Canada, 2012), though it is possible for policy to reverse this trend. As I'll note later, my research does not include the potential GHG reductions from a modal switch from trucking to rail – but does address the other three pathways. Below I discuss several policy options, noting which are being used in Canada or elsewhere.

First, fuel efficiency standards require freight suppliers to increase the average fuel efficiency of the fleet of freight vehicles. Fuel efficiency standards achieve freight GHG reductions through improved vehicle technologies. In 2014, the Federal Government of Canada imposed fuel efficiency standards for truck engines (*Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations*), and these regulations have recently been amended to increase in stringency until 2027 (Phase 2) (ICCT, 2017). These standards require freight suppliers to improve the average fleet fuel efficiency of new trucks in the range of 9% to 25% by 2027 depending on regulatory category. Compliance of current fuel efficiency standards is expected through the adoption of more efficient diesel drivetrains, but these standards also allow compliance through the adoption of ZEVs (Lutsey, 2017). Canada's fuel efficiency standards for trucks are designed to closely align with the national standards from the United States (ICCT, 2017). Currently, China and Japan have also implemented fuel efficiency standards for heavy duty vehicles, and policies in the European Union and Mexico are under development (Miller et al., 2017).

Second, a carbon tax is a pricing scheme that is levied based on the carbon content of fuels. A carbon tax achieves freight GHG emissions through all four mitigation pathways, because higher energy costs incentivise reductions through any cost-effective means. The federal government has announced a federal carbon pollution pricing system, which will start at \$20/tCO2e in 2019 and increase to \$50 by 2022 (ECCC, 2017a). The federal carbon pricing system is a central component in the Pan-Canadian Framework on Clean Growth and Climate Change and is one of the highest carbon prices in the world (ECCC, 2017a). The province of British Columbia was the first jurisdiction in North America to implement a carbon tax in 2008, which started at \$10//tCO2e and increased to \$35//tCO2e in 2018 (Government of British Columbia, N.D.). Currently, 65 jurisdictions around the world, representing about 15% of global GHG emissions, have enacted a carbon pricing scheme (Government of British Columbia, N.D.).

Third, a low carbon fuel standard (LCFS) requires fuel suppliers to reduce the average carbon intensity (gCO2e/GJ) of fuels they supply. A LCFS achieves freight GHG reductions through the mitigation pathway of reducing GHGs associated with fuels. The average carbon intensity can be decreased by blending renewable fuels with conventional ones, supplying less carbon intensive and more zero tailpipe emission fuels, and by decreasing the emissions associated with the production of fuels. Currently, the province of British Columbia and the State of California have LCFS policies enacted that require fuel suppliers to decrease the average WTW carbon intensity of their fuels by 10% in 2020, and these governments are in the process of setting targets for 2030 and beyond (Government of British Columbia, N.D.; California Air Resources Board, 2018). The Government of Canada has proposed the enactment of a federal Clean Fuel Standard (otherwise know as a LCFS) as part of the Pan-

Canadian Framework on Clean Growth and Climate Change. The proposed standard would require fuel suppliers to reduce WTW carbon intensity of fuels by 10% to 15% by 2030 (Government of Canada, 2017). The federally proposed LCFS has emerged as one of the most promising and significant initiatives within the suite of Pan-Canadian Framework policies (Plumptre et al., 2017). In Europe, the European Union Fuel Quality Directive requires fuel suppliers to reduce WTW carbon intensity by 10% by 2020, but only 6% is binding; 2% can attained using carbon sequestration and storage and 2% can be achieved through emissions trading schemes (Government of Canada, 2017).

Fourth, a Zero-Emission Vehicle (ZEV) Mandate requires automakers to sell a minimum percentage of ZEVs. A ZEV mandate targets freight GHG emissions through improved vehicle technologies. This type of policy requires that a certain percentage of new vehicle sales are ZEVs. Several jurisdictions, including 10 US states, the province of Quebec and China, have ZEV mandates that apply to passenger vehicles, but no such policy exists for the sale of ZEV freight technologies. However, a ZEV mandate for trucks has been identified as a feasible policy tool to promote the adoption of ZEVs and reduce freight GHG emission (Fulton et al., 2015; den Boer et al, 2013).

Finally, a purchase subsidy (or rebate) reduces the price paid by consumers and could be applied to more efficient or ZEV freight technologies. In California, the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program (HVIP) provides a point-of-sale price incentive on the purchase of clean trucks and busses (HVIP, 2018). This subsidy is expected to help accelerate the growth of early market of zero-emission and hybrid trucks and buses by 30 percent (HVIP, 2018). This subsidy ranges from $60,000 to $80,000 for zero emission trucks.

1.3. Modeling the Freight Sector

Quantitative models have been used investigate how different policy, technological and economic assumptions impact future GHG emissions. In the transportation sector, such models have been used to assess the impacts of different climate policy scenarios, but modeling of the transportation sector has tended to focus on passenger vehicles and has neglected freight vehicles (Mccollum et al., 2009). Research focusing on freight transportation has primarily used static accounting tools, in which lifecycle GHG emissions are analyzed for different freight technologies to predict

GHG emissions under different technical assumptions. Research by Environment and Climate Change Canada (2017) modelled the impact of currently enacted policies on freight GHG emission until 2030 using an optimization model, in which gross domestic product is maximised based on energy data and policy constrains. Finally, some studies have used simulation models that represents technological change, behavioral dynamics, as well as feedbacks among economic sectors to simulate freight GHG emissions under different policy scenarios at the federal and British Columbia provincial levels. In this section I review the research completed in each of these areas.

Research by Moultak et al. (2017), Talebian et al. (2018), den Boer et al. (2013) and Fulton et al (2015) using static accounting tools have assessed lifecycle GHG emissions under different technological scenarios. Static accounting research is useful in determining what technological scenarios could lead to significant decarbonization in freight but fails to address the question of which policies are needed to achieve the technology uptake shown in these scenarios. For example, research by Talebian et al. (2018) and Moultak et al. (2017) found that even under fuel efficiency standards requiring the adoption of the best available fuel efficiency technologies for diesel trucks, emissions will only decrease by 10% to 20% relative to 2005 levels. Along with Talebian, et al. (2018) and Moultak et al. (2017), other researchers (den Boer et al., 2013; Fulton et al, 2015) have found that the adoption of ZEV trucks will be required to achieve significant reduction in freight. These researchers illustrate scenarios where high adoption (65% of market share or above of ZEV trucks) of battery electric and hydrogen fuel cell vehicles leads to deep decarbonization (reductions ranging from 40%-80%). Talebian et al. (2018) found that WTW GHG reductions of 64% in British Columbia were possible, but more than 65% of freight trucks would have to run on all-electric drivetrains. Although this stream of research did not simulate the impacts of climate policies, Moultak et al. (2017) and Fulton et al. (2015) concluded that there is no “Silver Bullet” policy for achieving deep decarbonization in the freight sector (that is, no single policy can alone achieve climate goals), and policies targeting both ZEV uptake and the production low carbon fuels will likely be needed.

In Canada’s 3rd Biennial Report on Climate Change (ECCC, 2017), an optimization model is used to simulate the freight GHG emissions until 2030 under the currently enacted policies (i.e. federal fuel efficiency standards for trucks). Under this policy scenario, freight emissions are simulated to increase by 15% in 2030 compared to

2005 levels. Modelling results from this study highlight the inadequacy of current policies and the need to enact further policies to achieve freight GHG reductions. However, the model does not show the impacts of presently proposed policies (i.e. carbon pricing scheme and clean fuel standard) or more stringent policies.

Several studies have used simulation models to explore the impacts of different policy scenarios aimed at reducing freight emissions. Using a hybrid energy-economy model, CIMS, research by Jaccard et al. (2016) and Vass (2016) modelled the effects of climate policies aimed to reduce economy wide GHG emissions to achieve Canada's 2050 reduction goal (i.e. 80% reduction relative to 2005 levels), including scenarios with policies targeting freight emissions. Freight emissions were simulated under four policy scenarios (i.e. current enacted policies, addition of the federal carbon price, a carbon price rising to $200/tonne in 2030 and a LCFS reaching 80% reduction in fuel carbon intensity by 2040 with the federal carbon price) until 2050. The federal carbon price was found to be ineffective in reducing freight GHG emissions. Emissions reductions in 2050 compared to 2005 levels resulting from a carbon price rising to $200 in 2030 ranged from 30% to 60%. Under the LCFS reaching 80% reduction in fuel carbon intensity by 2040 with the federal carbon price scenario, freight GHG reduction goals are achieved.

Research by Lepitzki et al. (2018) modelled the effect of different policy packages in British Columbia's transportation sector - specifically, packages that included a LCFS - using an Excel-based simulation model (based on CIMS algorithms) tied to a fuel supply optimization model. Results from Lepitzki et al. (2018) indicate that achieving GHG reduction goals in British Columbia's freight sector will require a combination of stringent policies, which include an ambitious carbon tax, freight fuel efficiency standards, LCFS, and ZEV mandate for trucks. As well, Lepitzki et al. (2018) found that a LCFS played an additive role, in that it had an incremental impact on GHG reductions, as part of a package of policies targeting freight emission. Freight seemed to particularly benefit from a LCFS (whereas the passenger vehicle sector could still achieve climate targets without an LCFS).

1.4. Research Objectives and Approach

To improve insights into the effectiveness of policies aimed at reducing freight GHG emissions, I simulate the land freight (trucks and trains) sector out to 2050 using a technology adoption model (CIMS-Freight) that is both technologically explicit and behaviourally realistic. The federal government has recently announced the enactment of a carbon price scheme and their intent to enact a LCFS. My research provides insight into the effectiveness of the addition of these policies. As well, I run a series of policy scenarios to explore the effectiveness of several individual policies. Finally, I identify policy packages that have a high probability of achieving Canada's 2050 GHG targets of an 80% GHG reduction relative to 2005 levels. To account for uncertainty, I include a Monte Carlo Analysis in which uncertain model parameters are assigned a probability distribution based on their uncertainty, and a number of iterations are performed to reflect variability in uncertain model input parameters.

In summary, my research objectives are as follows:

- *Objective 1*: Use CIMS-Freight to simulate the likely impacts of Canada's current and proposed policies on GHG emissions in the freight sector (relative to 2030 and 2050 GHG targets).
- *Objective 2:* Identify several low-carbon freight policies and use CIMS-Freight to simulate their potential individual GHG impacts out to 2050.
- *Objective 3*: Simulate a number of regulation combinations (fuel efficiency standards, LCFS and ZEV mandate) to identify scenarios that have a high probability (i.e. at least 67% of Monte Carlo iterations) of achieving 2050 targets in the land freight sector.

Chapter 2. Methods

To achieve my research objectives, I simulate policy scenarios aimed at reducing GHG emissions from land freight in Canada using an Excel-based freight vehicle choice model (CIMS-Freight). CIMS-Freight simulates how climate policy scenarios influence the adoption of land freight technologies in five-year increments until 2050. The simulated market share for freight technologies is used to calculate WTW GHG emissions under different policy assumptions. This chapter explains the exogenous inputs and endogenous functions I use in CIMS-Freight.

I incorporate a Monte Carlo Analysis to represent uncertainty in CIMS-Freight by providing insight on how output values (i.e. WTW GHG emissions) vary depending on differing values of uncertain input parameters (i.e. future fuel prices). I perform a Monte Carlo Analysis using the @Risk add-on for Excel. In the Monte Carlo Analysis, uncertain input model parameters are assigned a probability distribution based on their possible variability (I use normal distributions with a standard deviation) (Morgan et al., 1990). Output values are run through 1000 iterations to represent how uncertainty in input parameters translate into uncertainty in output values (i.e., GHG emissions).

2.1. Output and Market Share Competition

In CIMS-Freight, output is measured in tonne kilometers (TKM and is set exogenously for the three distinct land freight modes (light/medium trucks, heavy trucks and rail). A TKM represents the transport of one tonne of freight goods over one kilometer. Freight trucks are categorized based on their weight in Classes ranging from 2B to 8. Light/medium trucks range from Class between 2B and 6 and heavy trucks include Class 7 and 8. Within each mode total output is satisfied by different freight technologies which compete for market share. The exogenously set modes of freight do not allow for substitution. Thus, my model does not capture modal switch between heavy trucks and rail or light/medium trucks and heavy trucks, which is a possible policy outcome. Initial values for output per mode are based on historical data from Environment and Climate Change Canada (ECCC) (2017). I set the output growth rate for each mode of freight exogenously based on simulated annual growth rates from

ECCC (2017), which are 0.6% for rail, 1.7% for light/medium trucks and 1.5% for heavy trucks.

TKM is firstly fulfilled by the existing stock of freight vehicles (vehicles purchased in previous time periods) and remaining output is fulfilled by new market share. The new market share meets the demand not satisfied by existing stock, due to the retirement of vehicles and changes in total output per mode. For light/medium trucks, I base vehicle retirement rates on data from Davis et al. (2015) that estimates that approximately 10% of vehicles retire after 5 years, 30% after 10 years and 100% after 15 years from year of purchase. I base heavy trucks retirement rates on data from Davis et al. (2015) that estimates that 10% retire after 5 years, 25% after 10 years, 60% after 15 years, and 100% after 20 years from year of purchase. For rail technologies, I base the retirement schedule on a life expectancy of 20 years (U.S. DOT, 2014).

In CIMS-Freight, a vehicle's life cycle costs are based on the financial costs, as well as the perceived intangible costs associated with each technology (Equation 1).

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

Life cycle costs are based on upfront capital cost (CCj), upfront intangible cost (ij), annual energy costs (ECj) and annual maintenance costs (MCj). A discount rate is used to annualize costs across a technology's lifespan. A social discount rate is appropriate for making choices and setting policy in a societally optimal manner, whereas a private discount rate is appropriate when trying to simulate the private calculations and decision making by end consumers (Fulton et al., 2015). Other freight researchers (Fulton et al., 2015; den Boer et al., 2013; Moultak et al., 2017) have used a social discount rate of 4% in assessing the future costs of freight technologies. However, I use a private discount rate to represent the private decisions of freight suppliers. The use of high private discount rates places more value on short-term costs and benefits than future ones, which limits the impact future fuel savings have on overall costs and restricts investment in non-conventional freight technologies with longer payback periods (Fulton et al., 2015). Similar to other modelling studies (Lepitzki et al., 2018; Cooper et al., 2009; Ricardo Energy and Environment, 2017), I assign a baseline private discount rate of 8%. Given the uncertainty of this parameter value, I include discount rate as an uncertain parameter value in my Monte Carlo Analysis with a normal distribution and a standard deviation of 30%.

Available freight technologies compete for new market share based on the CIMS market share competition algorithm (Rivers & Jaccard, 2006) (Equation 2).

$$\boldsymbol{MS_j} = \frac{\boldsymbol{LCC_j^{-v}}}{\sum_{\boldsymbol{k=1}}^{\boldsymbol{K}}\{\boldsymbol{LCC_K^{-v}}\}} \qquad \textbf{(}\text{Equation 2)}$$

Equation 2 calculates new vehicle market share for each mode based on the relative life cycle costs ($LCCj$) associated with each available technology. The market heterogeneity parameter (v) is used to reflect how costs are perceived amongst different consumers (Jaccard, 2009). For example, the owner of a delivery truck travelling long distances each day would place a higher value on a vehicle with a longer range (distance between refueling) compared to a small delivery truck that makes only local deliveries. Market heterogeneity values typically range from 4 to 25 (Vass, 2016). High values indicate a homogenous market in which technologies with the lowest life-cycle costs will capture the most market share. Low values indicate a heterogeneous market in which new market share will be more divided amongst the different technologies in an attempt to capture consumers' different perception of costs amongst technologies. Typically, industrial and commercial sectors are assigned a higher market heterogeneity value compared to consumer sectors (Jaccard, 2009), but research has found some heterogeneity in the usage and travel characteristics of freight vehicles (Winebrake et al, 2012; Fulton et al., 2015). I assign a baseline value of 15, which is in line with what Lepitzki et al. (2018) and Vass (2016) in their studies used to represent freight. I include this value as an uncertain parameter in my Monte Carlo Analysis with a normal distribution and standard deviation of 30%.

For overall TKM, I incorporate an own-price elasticity feedback that adjusts demanded output to account for changes in energy costs in scenarios where certain policies impact energy prices (e.g. a carbon tax increases the cost of carbon intensive fuels, such as diesel). For example, higher fuel costs would increase shipping costs which could thus encourage consumers to purchase items that do not need to be shipped as far. In CIMS-Freight, the baseline own-price elasticity is set to -0.3 (e.g., a 100% increase in energy costs of freight results in a 30% decrease in output) based on research by Litman (2018) in which freight elasticities were empirically estimated.

2.2. Vehicle Technologies

Table 2.1 summarizes the different vehicle drivetrains available per freight mode and the eligible fuels for each technology. For each mode, I include diesel, electric, hydrogen, biodiesel, and natural gas (both compressed natural gas (CNG) and liquefied natural gas (LNG)) drivetrain technologies. As well, I include more efficient diesel drivetrains**.** In terms of difference across modes, I only include gasoline drivetrains under the light/medium mode. Plug-in hybrid trucks have both a diesel and electric drivetrain, which limits battery size (i.e. limited electric ranges). I only include plug-in hybrid drivetrains under light/medium trucks due to the heavy cargo weight, large size and long-distance travel requirements of heavy trucks and rail (assuming there are only very limited battery range in heavy truck and rail plug-in hybrids). I include battery electric trucks in both the light/medium truck and the heavy truck mode, but I do not include electric trucks fueled by catenary wires (catenary technology is only modeled as being available for rail). For drivetrains that have different fuel options, fuel choice is determined based on the mix that minimizes energy costs within technological constraints (i.e. blend wall of biodiesel in diesel drivetrains and limited electric range of plug-in hybrid trucks). For more information regarding fuel characteristics and fuel competition refer to *Section 2.3: Fuels*. For each technology in CIMS-Freight, I assign vehicle parameters that determine the simulated market share under different scenarios. In the next sections, I summarize these parameter values.

Table 2.1 Available Vehicle Technologies and Fuel Type(s) used by mode

Drivetrain Technology	Fueling Options
Light/Medium Truck	
Gasoline	Gasoline or Ethanol Blend (up to 15%)
Diesel Standard	Diesel or Biodiesel Blend (up to 20%) or HDRD
Medium Efficiency	Diesel or Biodiesel Blend (up to 20%) or HDRD
High Efficiency	Diesel or Biodiesel Blend (up to 20%) or HDRD
Hybrid	Diesel or Biodiesel Blend (up to 20%) or HDRD
LNG	LNG only
CNG	CNG only
Hydrogen Fuel Cell	Hydrogen only
Battery Electric	Electricity only
Plug- in hybrid	Electricity or Diesel or Biodiesel Blend (up to 20%) or HDRD
Biodiesel	Diesel or Biodiesel (up to 100%) or HDRD
Heavy Truck	
Diesel Standard	Diesel or Biodiesel Blend (up to 20%) or HDRD
Medium Efficiency	Diesel or Biodiesel Blend (up to 20%) or HDRD
High Efficiency	Diesel or Biodiesel Blend (up to 20%) or HDRD
Hybrid	Diesel or Biodiesel Blend (up to 20%) or HDRD
LNG	LNG only
CNG	CNG only
Hydrogen Fuel Cell	Hydrogen only
Biodiesel	Diesel or Biodiesel (up to 100%) or HRD
Battery Electric	Electricity only
Rail Freight	
Existing	Diesel or Biodiesel Blend (up to 20%) or HDRD
Medium Efficiency	Diesel or Biodiesel Blend (up to 20%) or HDRD
Hybrid	Diesel or Biodiesel Blend (up to 20%) or HDRD
LNG	LNG only
CNG	CNG only
Biodiesel	Diesel or Biodiesel (up to 100%) or HDRD
Hydrogen Fuel Cell	Hydrogen only
Catenary Wire	Electricity only

*Biodiesel (up to 20% blend) based on National Biodiesel Board (2016)
*HDRD (up to 100% blend) based on Aatola et al. (2008); Lapuerta et al. (2011); Nylund et al. (2011)
*Ethanol (up to 15%) based on Iowa Renewable Fuels Association (2019)

2.2.1. Capital Costs

Upfront Capital Costs

Capital costs for diesel and gasoline truck technologies are set based on research by Moultak et al. (2017), Fulton et al. (2015) and Den Boer et al. (2013), and for diesel rail technologies capital costs are based on information from Sterling Rail Inc. (2017) (see Table 2.2). The capital costs associated with more fuel efficient diesel drivetrains (improvements ranging from 10%-40%) are based on assumptions from the U.S. Energy Information Administration (2016) for trucks and U.S. Department of Transportation (2014) for rail. I base the capital costs for LNG, CNG, biodiesel, battery electric and hydrogen fuel cell trucks on research by Moultak et al. (2017), Fulton et al. (2015) and den Boer et al. (2013).

Table 2.2 Capital Cost Parameters

Drivetrain Technology	Capital Costs 2015 (CAN$)	Endogenous Progress Ratio*	Exogeneous Progress Ratio*	Sources
Light/Medium Truck				
Gasoline	$200,000	1	1	Moultak et al.(2017), Fulton et al.(2015)
Diesel Standard	$200,000	1	1	Moultak et al.(2017), Fulton et al.(2015)
Medium Efficiency	$208,000	1	1	U.S. EIA (2016)
High Efficiency	$215,000	1	1	U.S. EIA (2016)
Hybrid	$230,000	~N(0.99, 0.05)	~N(0.99, 0.05)	Moultak et al.(2017), Fulton et al.(2015)
LNG	$235,000	~N(0.97, 0.05)	~N(0.97, 0.05)	Moultak et al.(2017), Fulton et al.(2015)
CNG	$220,000	~N(0.97, 0.05)	~N(0.97, 0.05)	Moultak et al.(2017), Fulton et al.(2015)
Hydrogen Fuel Cell	$350,000	~N(0.93, 0.05)	~N(0.93, 0.05)	Moultak et al.(2017), Fulton et al.(2015)
Battery Electric	$400,000	~N(0.93, 0.05)	~N(0.93, 0.05)	Moultak et al.(2017), Fulton et al.(2015)
Plug- in hybrid	$270,000	~N(0.97, 0.05)	~N(0.97, 0.05)	Moultak et al.(2017), Fulton et al.(2015)
Biodiesel	$215,000	~N(0.97, 0.05)	~N(0.97, 0.05)	Moultak et al.(2017), Fulton et al.(2015)
Heavy Truck				
Diesel Standard	$220,000	1	1	Moultak et al.(2017), Fulton et al.(2015)
Medium Efficiency	$230,000	1	1	U.S. EIA (2016)
High Efficiency	$240,000	1	1	U.S. EIA (2016)
Hybrid	$255,000	~N(0.99, 0.05)	~N(0.99, 0.05)	Moultak et al.(2017), Fulton et al.(2015)
LNG	$260,000	~N(0.97, 0.05)	~N(0.97, 0.05)	Moultak et al.(2017), Fulton et al.(2015)
CNG	$240,000	~N(0.97, 0.05)	~N(0.97, 0.05)	Moultak et al.(2017), Fulton et al.(2015)
Hydrogen Fuel Cell	$380,000	~N(0.92, 0.05)	~N(0.92, 0.05)	Moultak et al.(2017), Fulton et al.(2015)
Biodiesel	$240,000	~N(0.97, 0.05)	~N(0.97, 0.05)	Moultak et al.(2017), Fulton et al.(2015)
Battery Electric	$450,000	~N(0.92, 0.05)	~N(0.92, 0.05)	Moultak et al.(2017), Fulton et al.(2015)
Rail Freight				
Existing	$665,000	1	1	U.S. DOT(2014), Sterling Rail Inc.(2017)
Medium Efficiency	$680,000	1	1	U.S. DOT(2014), Sterling Rail Inc.(2017)
Hybrid	$1,000,000	~N(0.99, 0.05)	~N(0.99, 0.05)	U.S. DOT(2014), Sterling Rail Inc.(2017)
LNG	$1,050,000	~N(0.97, 0.05)	~N(0.97, 0.05)	U.S. DOT(2014), Sterling Rail Inc.(2017)
CNG	$1,000,000	~N(0.97, 0.05)	~N(0.97, 0.05)	U.S. DOT(2014), Sterling Rail Inc.(2017)
Biodiesel	$850,000	~N(0.97, 0.05)	~N(0.97, 0.05)	U.S. DOT(2014), Sterling Rail Inc.(2017)
Hydrogen Fuel Cell	$1,800,000	~N(0.93,0.05)	~N(0.93,0.05)	U.S. DOT(2014), Sterling Rail Inc.(2017)
Catenary Wire	$1,800,000	~N(0.95, 0.05)	~N(0.95, 0.05)	U.S. DOT(2014), Sterling Rail Inc.(2017)

*~N(0.99, 0.05) refers to the use of a normal distribution and the values in parentheses represent the median and the standard deviation values

Declining Capital Costs

The declining capital cost feature of CIMS-Freight represents exogenous and endogenous technological change by simulating how the capital costs for new technologies will decrease over each 5-year simulation period. As manufacturers gain experience producing a technology, the costs of production will decrease, which is referred to as “learning by doing” (Löschel, 2002). As well, manufactures can save on costs through economies of scale (cost savings from increasing production levels) when a technology becomes more widely adopted. CIMS-Freight includes both endogenous and exogenous decline in capital costs.

In CIMS-Freight, the endogenous decline in capital costs is based on the following function:

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

The endogenous decline in capital cost function simulates how cumulative production for each technology within Canada impacts the capital costs in each simulation period ((t)). The endogenous declining capital costs are based on initial capital costs in 2015 ($CC_j(t_0)$), simulated cumulative production for a technology within the model (Nj), and the endogenous progress ratio (PRj). Cumulative production of a technology is based on the simulated demand for each technology and acts as a proxy for production experience within the model. The endogenous progress ratio is a measure of the extent to which a vehicle’s capital costs will decrease with a doubling in simulated cumulative production of a technology relative to the prior simulation period (Jaccard, 2009).

The exogenous annual capital decline rate is the percentage decline in capital costs that occurs regardless of changes to simulated cumulative production in Canada. The exogenous decline in capital costs accounts for technological spillover from production outside of Canada. Canada is not isolated from the rest of the world, and technological innovations in other countries can reduce the price of technologies within Canada (Sykes et al, 2017).

Based on research that simulates future capital costs of freight technologies, I adjusted the endogenous progress ratio and exogenous annual capital decline rate so that simulated future capital costs align with research by Moultak et al. (2017), Fulton et al. (2015) and den Boer et al. (2013). I set the endogenous progress ratio and exogenous annual capital decline as unknown parameters in my Monte Carlo Analysis given the uncertainty in future costs of freight technologies. The notation in Table 2.2 indicates that in the Monte Carlo Analysis I use a normal distribution (~N), and the values in parentheses represent the median and the standard deviation values, respectively.

2.2.2 Intangible costs

I infer relative intangible costs for each drivetrain based on literature that examines barriers to freight vehicle adoption, and further adjust intangible costs to calibrate CIMS-Freight to align with historical and simulated GHG emissions and freight vehicle technology market shares (ECCC, 2017) (Table 2.3). Intangible costs reflect the non-financial costs associated with a new technology, which includes the perceptions of quality, reliability, availability, social desirability or popularity (Axsen et al, 2009). I focus on four categories: availability of fuel, availability of drivetrain, refuel time/ range and perception of risk. I chose these four categories because they capture the range of non-financial barriers identified in the literature for the adoption of different freight drivetrain technologies (Moultak et al., 2017; Fulton et al., 2015; den Boer et al., 2013) and the adoption of more fuel efficient diesel drivetrains (Roeth et al., 2013). The approximate scale for intangible costs is largely based on values that are required for simulated outputs to align with output of ECCC (2017) research, and literature on barriers to adoption of freight technologies is used to inform relative intangible costs across drivetrains.

Fuel availability, in terms of supply and infrastructure, varies across fuel types. Gasoline and diesel fuels are widely available and an extensive network of refueling infrastructure exists for these fuels. Thus, I set no intangible costs for the fuel availability category of diesel and gasoline drivetrains. According to Natural Resource Canada (2018), in Canada there are 36 public stations that supply CNG, five that supply LNG, four that supply hydrogen and four that supply a high blend of biodiesel (20% and above). The lack of availability of natural gas, hydrogen, and biodiesel is represented as an intangible cost associated with the adoption of these drivetrains. Although there are limited natural gas refueling stations, there is natural gas infrastructure in place across Canada, including a network of pipelines that transport natural gas across the country

(Natural Resource Canada, 2018a). Given that biofuels are available in liquid form and refuelling occurs in the same manner as diesel, existing diesel infrastructure can use biofuels with little to no modifications (Natural Resource Canada, 2015). Hydrogen fuel cell truck drivetrains have the highest intangible costs for the fuel availability category given the lack of existing infrastructure compared to natural gas and other fuels, and the need to develop a new refueling infrastructure network, unlike biodiesel. Electricity is readily available, but electric freight infrastructure is limited (i.e. fast charging stations for battery electric trucks). Electric rail powered by catenary wires will require significant infrastructure network before vehicle deployment, which is represented in intangible costs of $130,000 for the fuel availability intangible cost category.

The widespread availability of new freight technologies can be limited (i.e. limited production, few manufactures, restricted by truck class), which is a barrier to the adoption of these new technologies (Moultak et al., 2017). Natural gas freight drivetrains are commercially available in almost all classes of truck, but their widespread availability for purchase (e.g. at a dealership) is limited compared to conventional diesel technologies (Fulton et al., 2015). Thus, for natural gas technologies, I assign intangible costs of $5000 for light/medium trucks and $7500 for heavy trucks. Although electric, hydrogen and biodiesel freight technologies are being produced, developed and announced by long established and new start-up freight companies, widespread commercialization and large-scale production have not occurred, which restricts availability (Moultak et al., 2017). Thus, I assign similar intangible costs for these drivetrains in terms of widespread availability.

Long refuel times and short vehicle ranges can increase the time associated with freight delivery, and this added time is an intangible cost that freight suppliers take into consideration when making decisions (Nealer et al., 2009). Refuel times and vehicle range for hydrogen, CNG and biodiesel freight technologies are comparable to those of diesel and gas (Moultak et al., 2017; Fulton et al., 2015; Den Boer et al., 2013). Thus, I assign these technologies no intangible costs for the refuel times and vehicle range intangible cost category. LNG must be stored at minus 160 degrees Celsius, which can cause freezing. This freezing can cause delays in refueling times (Natural Resource Canada, 2018b), which I reflect by assigning intangible costs of $3000 for the refuel times and vehicle range intangible cost category. Intangible costs, for electric trucks are largely due to their short range and long refuel times compared to conventional diesel technologies (Fulton et al., 2015). As well, these intangible costs are more pronounced for heavy electric trucks than light/medium trucks, because heavy trucks typically travel farther distances and have heavier loads (Moultak et al., 2017; Fulton et al., 2015; Den Boer et al., 2013).

Consumers perceive an extra risk for the adoption of new technologies and/or technologies with limited market penetration. Consumers have limited exposure and experience, and as a result, are more reluctant to adopt “unproven” technologies (Rivers, 2000). Diesel technologies account for nearly all the current market share, and as a result, are perceived as having little risk. I assign modest intangible costs for more efficient diesel drivetrains (e.g. drivetrains with a hybrid system or auxiliary power unit) to account for lack of familiarity with more fuel efficient drivetrains while recognizing familiarity with diesel vehicles. Natural gas trucks have been available since the early 1990s (Sinor et al., 1992), but only small number of natural gas vehicles are in operation today. Thus, I assume there is some familiarity with natural gas technologies, but a significant risk premium still exists (i.e. $20,000 for light medium trucks and $30,000 for heavy trucks). Only a limited number of electric, hydrogen and biodiesel trucks are in operation today (less than natural gas drivetrains) (Fulton et al., 2015; Den Boer et al., 2013). Thus, consumers will have limited exposure and experience with these technologies and will likely perceive significant extra risk associated with their adoption.

Table 2.3 Intangible Costs by Technology

Technology	Availability of Fuel ($)	Availability of Drivetrain ($)	Refuel Time/ Range ($)	Perception of risk ($)	Total Initial Intangible Costs ($)
Light/Medium Truck					
Gasoline	0	0	0	0	0
Diesel Standard	0	0	0	0	0
Medium Efficiency	0	0	0	2000	2,000
High Efficiency	0	0	0	3000	3,000
Hybrid	0	2,000	0	4000	6,000
LNG	50,000	5,000	3000	20,000	78,000
CNG	40,000	5,000	0	20,000	65,000
Hydrogen Fuel Cell	70,000	10,000	0	30,000	110,000
Battery Electric	15,000	10,000	55,000	30,000	110,000
Plug-in hybrid	5,000	10,000	0	10,000	25,000
Biodiesel	40,000	10,000	0	20,000	70,000
Heavy Truck					
Diesel Standard	0	0	0	0	0
Medium Efficiency	0	0	0	3500	3,500
High Efficiency	0	0	0	4500	4,500
Hybrid	0	3,000	0	5500	8,500
LNG	70,000	7,500	3000	30,000	110,500
CNG	60,000	7,500	0	30,000	97,500
Hydrogen Fuel Cell	110,000	15,000	0	40,000	165,000
Biodiesel	60,000	15,000	0	30,000	105,000
Battery Electric	20,000	15,000	100,000	40,000	175,000
Rail Freight					
Existing	0	0	0	0	0
Medium Efficiency	0	0	0	5000	5,000
Hybrid	0	5,000	0	10,000	15,000
LNG	70,000	15,000	0	30,000	115,000
CNG	60,000	15,000	0	30,000	105,000
Biodiesel	60,000	15,000	0	30,000	105,000
Hydrogen Fuel Cell	110,000	15,000	0	40,000	165,000
Catenary Wire	130,000	10,000	0	10,000	130,000

As technologies become more widely adopted, intangible costs tend to decrease. For example, consumers gain experience with new technologies, share information and availability increases. CIMS-Freight incorporates these effects using the following function:

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

The declining intangible cost function is used to calculate a technology's intangible cost for a given period ((t)). A technology's declining intangible cost is calculated based on the technology's initial intangible cost (i_j), its market share in the previous period ($(t-1)$), and the declining intangible cost rates (*A* and *k*). The declining intangible cost rates (*A* for shape of function and *k* for rate of function) are fixed and determine the extent to which intangible costs decrease with increased market share. I assign values (*A*=40 and *k* = 0.0065) in line with those used by Lepitzki et al. (2018) and Vass (2016) in assessing freight declining intangible costs. Based on my judgement I found that declining intangible costs seemed appropriate under these rates.

2.2.2. Fuel Efficiency (GJ/TKM)

In CIMS-Freight, fuel efficiency is a measure of the amount of energy used per TKM, which I set exogenously for each drivetrain technology (see Table 2.4). Fuel efficiency values vary across the different drivetrains (e.g. natural gas drivetrains are less efficient than standard diesel whereas electric and hydrogen drivetrains are more efficient). I assign fuel efficiency values across freight drivetrains based on values used by den Boer et al. (2013) and Moultak et al. (2017) who calculate freight GHG emissions using a static accounting tool under different technological scenarios. As well, I include a number of more efficient diesel drivetrains and use fuel efficiency values from the U.S. Energy Information Administration (2016) who examine the incremental fuel efficiency improvements from available fuel efficiency technologies.

Table 2.4 Fuel Efficiency (MJ/TKM) of different Drivetrain Technologies

Drivetrain Technology	Fuel Efficiency (MJ/TKM)	Source
Light/Medium Truck		
Gasoline	1.55	den Boer et al. (2013), Moultak et al. (2017)
Diesel Standard	1.5	den Boer et al. (2013), Moultak et al. (2017)
Medium Efficiency	1.35	U.S. EIA (2016)
High Efficiency	1.22	U.S. EIA (2016)
Hybrid	1.08	U.S. EIA (2016)
LNG	1.6	den Boer et al. (2013), Moultak et al. (2017)
CNG	1.6	den Boer et al. (2013), Moultak et al. (2017)
Hydrogen Fuel Cell	1.05	den Boer et al. (2013), Moultak et al. (2017)
Battery Electric	0.8	den Boer et al. (2013), Moultak et al. (2017)
Plug-in hybrid	1.25	den Boer et al. (2013), Moultak et al. (2017)
Biodiesel	1.58	den Boer et al. (2013), Moultak et al. (2017)
Heavy Truck		
Diesel Standard	0.92	den Boer et al. (2013), Moultak et al. (2017)
Medium Efficiency	0.83	U.S. EIA (2016)
High Efficiency	0.74	U.S. EIA (2016)
Hybrid	0.64	U.S. EIA (2016)
LNG	0.96	den Boer et al. (2013), Moultak et al. (2017)
CNG	0.96	den Boer et al. (2013), Moultak et al. (2017)
Hydrogen Fuel Cell	0.6	den Boer et al. (2013), Moultak et al. (2017)
Biodiesel	0.95	den Boer et al. (2013), Moultak et al. (2017)
Battery Electric	0.55	den Boer et al. (2013), Moultak et al. (2017)
Rail Freight		
Existing	0.13	den Boer et al. (2013), Moultak et al. (2017)
Medium Efficiency	0.11	U.S. EIA (2016)
Hybrid	0.09	U.S. EIA (2016)
LNG	0.15	den Boer et al. (2013), Moultak et al. (2017)
CNG	0.15	den Boer et al. (2013), Moultak et al. (2017)
Biodiesel	0.14	den Boer et al. (2013), Moultak et al. (2017)
Hydrogen Fuel Cell	0.08	den Boer et al. (2013), Moultak et al. (2017)
Catenary Wire	0.06	den Boer et al. (2013), Moultak et al. (2017)

2.3. Fuels

CIMS-Freight contains nine fuels: diesel, gasoline, biodiesel, HDRD, ethanol, CNG, LNG, electricity and hydrogen. Certain freight technologies can use more than one fuel, which gives freight suppliers some flexibility to choose the fuel mix. In contrast, some drivetrains are limited to one fuel (i.e. battery electric, hydrogen fuel cell and natural gas drivetrains). In CIMS-Freight, suppliers choose the fuel mix that minimizes their energy costs. However, the fuel mix is constrained by technological characteristics. Diesel can be blended with biodiesel and HDRD and used in diesel drivetrains. The amount of blending is constrained by a “blend wall.” For biodiesel, I assume the blend wall is 20%, because 70% of the major diesel engine manufacturers in the United States have approved the use of B20 (i.e. 20% biodiesel, 80% diesel) (National Biodiesel Board, 2016). Research suggests that diesel drivetrains can run on 100% HDRD with small or no modifications (Aatola et al., 2008; Lapuerta et al., 2011; Nylund et al., 2011). Thus, I assume HDRD has no blend wall with conventional diesel drivetrains. In the light/medium trucks node, the plug-in hybrid drivetrain can run on both electricity and diesel. However, due to the limited range of the battery that I assume for plug-in hybrids, I assume that the electric drivetrain can only be used for a maximum of 40% of kilometers travelled (Fulton et al., 2015).

The price and WTW carbon intensity for each fuel is set exogenously. However, policies can endogenously influence these fuel characteristics (e.g. carbon tax on fuel price). I set fuel prices and carbon intensities as uncertain input parameters in my Monte Carlo Analysis using normal distributions to help account for the uncertainty of future values of these parameters. The following sections review parameter values for fuel prices (summarized in Table 2.4) and WTW carbon intensities (summarized in Table 2.5). The standard deviation column in Table 2.4 and Table 2.5 is used to quantify the amount of variation in the Monte Carlo Analysis for each fuel type.

2.3.1. Fuel Prices

I assign diesel and gasoline prices based on crude oil price forecasts to 2050 by Brent Crude Oil (National Energy Board, 2016). The forecasts include a reference scenario, low price scenario and high price scenario. The standard deviation for the Monte Carlo Analysis is based on the variability in these three scenarios.

I base HDRD, biodiesel, and ethanol prices on estimates from the U.S. Department of Energy (2016) and Cazzola et al. (2013). Production costs for HDRD, biodiesel and ethanol vary depending on the source, but production costs for all sources of HDRD, biodiesel, and ethanol have not reached maturity (Cazzola et al, 2013). Thus, I assume that the relative price of HDRD, biodiesel, and ethanol compared to diesel decreases.

I set the price of natural gas (both LNG & CNG) based on forecasts from Henry Hub Natural Gas (National Energy Board, 2016). The forecasts include a reference scenario, a high price scenario and a low price scenario. The standard deviation for the Monte Carlo Analysis is based on variability in the three scenarios.

I set electricity prices based on the country's average electricity price (National Energy Board, 2016; Canadian Electricity Association 2010). Future electricity prices are based on Canada's Energy Future 2016 (National Energy Board, 2016).

I base the price of hydrogen on estimates from Cazzola et al. (2013), Dillich et al. (2012), and Genovese et al. (2007). Hydrogen production has not reached maturity and production costs for all methods are predicted to decrease as they mature (Cazzola et al., 2013; Genovese et al., 2007). Thus, I assume that they decrease over time.

Table 2.5 Fuel Prices ($/GJ)

Fuel:	2015	2020	2025	2030	2035	2040	2045	2050	Standard Deviation
Diesel	35	41	43	45	46	47	49	50	20%
Gasoline	35	39	41	43	44	45	46	48	20%
HDRD	45	51	53	55	53	52	52	52	40%
Biodiesel	45	51	53	55	53	52	52	52	40%
Ethanol	40	42	43	45	45	46	47	49	40%
LNG	14	14	15	16	17	18	19	20	20%
CNG	14	14	15	16	17	18	19	20	20%
Hydrogen	60	55	53	48	45	45	45	45	40%
Electricity	30	30	31	31	32	32	33	33	20%

2.3.2. Carbon Intensities

I set carbon intensities for diesel and gasoline based on values used in the GHGenius (version 5.05b) model. I assume that the carbon intensity remains constant across simulation periods due to the maturity of production methods.

I base initial carbon intensities for HDRD, biodiesel, and ethanol on values used in the GHGenius (version 5.05b) model. Currently, higher carbon intensive production methods are more cost effective, and thus are more common (Cazzola et al, 2013). However, the costs of production for less carbon intensive methods (e.g. corn) will likely decrease relative to more carbon intensive methods as production methods reach maturity (e.g. palm oil) (Cazzola et al, 2013). I assume that, over time, HDRD, biodiesel, and ethanol are increasingly produced from lower carbon sources. Admittedly, the presence of certain policies (e.g., a low-carbon fuel standard) would likely induce a further reduction in the carbon intensity of these fuels (which I do not model).

I assign carbon intensities for CNG and LNG based on values used in the GHGenius (version 5.05b) model. Vehicle technologies exist that use both LNG and CNG, so I assign carbon intensities for both. As well, I assume carbon intensity remain constant across simulation periods for natural gas.

I set carbon intensities for electricity based on values used in the GHGenius (version 5.05b) model. The simulated electricity mix in Canada is used to inform future carbon intensity values (National Energy Board, 2016). The use of renewables (e.g. hydro, solar) are predicted to increase in the future (National Energy Board, 2016); thus, I assume carbon intensities for electricity decrease over time.

I assign initial carbon intensities for hydrogen based on values used in the GHGenius (version 5.05b) model. Most of North America’s hydrogen supply is made through natural gas reformation, in which high temperature steam from the natural gas is used to produce hydrogen fuel (U.S. Department of Energy, 2016). However, hydrogen production through electrolysis, in which electrical energy and water as a material source is used to extract hydrogen molecules, is a promising less carbon intensive option (Cazzola et al., 2013; Genovese et al., 2007; California Air Resources Board, 2017). The production costs of hydrogen through electrolysis are predicted to decrease relative to production costs from natural gas reformation (Cazzola et al., 2013; Genovese et al., 2007). As a result, I assume production through electrolysis increases, which causes an associated reduction in carbon intensity values for hydrogen.

Table 2.6 WTW Carbon content (gCO2e/MJ)

Fuel:	2015	2020	2025	2030	2035	2040	2045	2050	Standard Deviation
Diesel	95	95	95	95	95	95	95	95	20%
Gasoline	88	88	88	88	88	88	88	0.88	20%
HDRD	95	90	85	80	75	70	65	60	40%
Biodiesel	95	90	85	80	75	70	65	60	40%
Ethanol	88	87	86	85	82	80	77	75	40%
LNG	65	65	65	65	65	65	65	65	20%
CNG	64	64	64	64	64	64	64	64	20%
Hydrogen	97	90	80	70	60	50	40	30	30%
Electricity	23	20	17	14	12	10	9	8	30%

2.4. Policy Scenarios and Assumptions

My first research objective focuses on simulating the impacts of current and proposed policies. The federal government has proposed a carbon tax (starting at \$20/tCO2e in 2018 and increasing to \$50 by 2022) (ECCC, 2017) and a LCFS (carbon intensity reductions of approximately 10-15% by 2030) (Government of Canada, 2016). I simulate the GHG emissions under four scenarios: i) No Policy, ii) Current, iii) Current + Tax and iv) Current + Tax + LCFS scenarios. The federal government has publicly announced their intent to enact a carbon price, whereas the LCFS is still under consideration. Thus, I focus on modeling the LCFS alongside the carbon price and current policies.

My second research objective involves simulating the effectiveness of individual low-carbon freight policies in reducing freight GHG emissions. To achieve my second research objective, I chose to simulate 5 low-carbon freight policies (fuel efficiency standards, carbon tax, LCFS, ZEV standard for trucks, and a subsidy) individually, each at three different stringencies. I select policy stringencies based what other researchers have used in similar modeling exercises, in part based on technological feasibility and/or political acceptability (sources noted below). The effectiveness of individual policies is directly influenced by stringency, which differs across policies. For example, the “Ambitious” ZEV mandate requires 100% new market share whereas the “Ambitious”

LCFS requires 75% reduction in carbon intensity. Thus, my ability to directly compare simulated effects across policies is limited. The policy assumptions and their stringency are summarized below (see Table 2.7*)*.

Table 2.7 Policy Stringencies for Fuel Efficiency Standards, Carbon Tax, LCFS, ZEV Mandate for Truck & Subsidy

Policy/ Stringency		2020	2025	2030	2035	2040	2045	2050
Fuel Efficiency Standards (% reduction in GJ/TKM from 2015)								
Current Fuel Efficiency Standards	Light/Medium Truck	8%	8%	13%	13%	13%	13%	13%
	Heavy Truck	15%	15%	20%	20%	20%	20%	20%
Moderate Fuel Efficiency Standards	Light/Medium Truck	8%	15%	20%	25%	30%	35%	35%
	Heavy Truck	15%	20%	25%	30%	35%	40%	45%
Ambitious Fuel Efficiency Standards	Light/Medium Truck	8%	15%	25%	35%	40%	45%	50%
	Heavy Truck	15%	25%	35%	40%	45%	50%	60%
Carbon Tax ($/tonne CO2e)								
Proposed Carbon Tax		$40	$50	$50	$50	$50	$50	$50
Moderate Carbon Tax		$40	$70	$80	$90	$100	$110	$120
Ambitious Carbon Tax		$50	$100	$150	$150	$150	$150	$150
LCFS (% reduction gCO2e/MJ of fuels supplied)								
Proposed LCFS		10%	12.5%	15%	15%	15%	15%	15%
Moderate LCFS		10%	15%	20%	25%	30%	35%	40%
Ambitious LCFS		10%	20%	30%	40%	50%	60%	75%
ZEV Mandate								
Weak ZEV Mandate		5%	10%	15%	20%	25%	30%	35%
Moderate ZEV Mandate		10%	20%	25%	35%	45%	55%	65%
Ambitious ZEV Mandate		15%	25%	30%	40%	60%	80%	100%
Subsidy ($/ZEV vehicle)								
Weak Subsidy		$60k/ $80k						
Moderate Subsidy		$60k/ $80k	$60k/ $80k	$60k/ $80k				
Ambitious Subsidy		$60k/ $80k	$60k/ $80k	$60k/ $80k	$60k/ $80k	$60k/ $80k	$60k/ $80k	$60k/ $80k

I simulate fuel efficiency standards at three stringencies (Current, Moderate, and Ambitious), in which the average fleet fuel efficiency of new truck purchases must comply with efficiency standards. To model fuel efficiency standards, I constrain the average fuel efficiency of adopted technologies at compliance levels and allow technologies to compete for market share within this constraint. The Current fuel efficiency standards scenario assumes the federal fuel efficiency standards remain in effect but do not increase in stringency (i.e. improvements of fleet fuel efficiency of new trucks in the range of 9% to 25% by 2027 depending on regulatory category). The Moderate stringency is based on research that estimates the future potential of advanced efficiency technologies (i.e. 40%–52% for heavy trucks and 30%–36% for light/medium trucks by 2030-2040) (Delgado et al., 2016). Finally, the Ambitious scenario is based on efficiency improvements slightly beyond predicted 2030-2040 efficiency potential of diesel technologies as estimated by Delgado et al. (2016) and compliance requires the adoption of ZEVs in later years.

I simulate a carbon tax at three stringencies (Proposed, Moderate and Ambitious). The carbon tax charge is applied to fuels in CIMS-Freight based on their respective WTW GHG emissions (refer to Table 2.6). The Proposed carbon tax scenario mimics the stringency of the proposed federal carbon tax (Environment and Climate Change Canada, 2017) but it assumes that stringency does not increase beyond $50/tCO2e. The Moderate tax scenario assumes that federal carbon tax is enacted and steadily rises to $120/tCO2 by 2050. Research by Lepitzki et al. (2018) and Sykes (2016) used a similar stringency to reflect a moderate carbon tax in research modelling the effect of climate policies in British Columbia's transportation sector. The Ambitious carbon tax scenario assumes that the stringency increases up to $150/tCO2 by 2030 where it remains constant.

I simulate a LCFS that is based on WTW carbon intensity at three stringencies (Proposed, Moderate and Ambitious). The exogenous representation of the fuel supply sector in CIMS-Freight limits how compliance is achieved, because it does not account for supply constraints, the influence that fuel suppliers have on the demand (e.g. cross-subsidization of zero tailpipe emission fuels) and the ability of fuel suppliers to comply by reducing production emissions. I model a LCFS simply by constraining the carbon intensity of fuel supplied at compliance levels and allow technologies and fuels to compete for market share within that constraint. The Proposed LCFS scenario is based on the stringency of a proposed federal LCFS (carbon intensity reductions of approximately 10-15% by 2030 compared to 2005) (Government of Canada, 2016). The Moderate and Ambitious LCFS scenarios are based on a modeling study by Lepitzki et al. (2018), in which the stringencies were chosen to cover a spectrum of potential carbon intensity reductions targets for 2050 in British Columbia.

I simulate a ZEV mandate for trucks that requires truck manufacturers to sell a minimum new market share of ZEVs at three stringencies (Weak, Moderate and Ambitious). To model a ZEV mandate, I restrict market share competition to only include ZEVs for the percentage of market share needed to comply with policy stringency (i.e. subtracting ZEV new market share that would occur without the mandate from policy requirement). Truck drivetrain technologies included under the ZEV mandate are battery electric, hydrogen fuel cell, and plug-in hybrid. I base the three stringency levels for a ZEV mandate on research by Lepitzki et al. (2018) that found these stringency levels to be in the realm of what is necessary to meet GHG targets in British Columbia's transportation sector.

I model a subsidy program at three stringencies (Weak, Moderate and Ambitious) by adjusting capital costs to reflect the addition of a subsidy. To model a subsidy, I adjust capital costs of subsidized technologies. Each scenario assumes that a total of $20 million is allocated per subsidy year. After the $20 million runs out, additional purchases do not include the subsidy. The Weak scenario adopts the current subsidy levels associated with California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program, but assumes the program is disbanded after 2020. The Moderate and Ambitious scenario assume that the subsidy is continued until 2030 and 2050 respectively.

My third research objective is to simulate policy combinations to identify scenarios that have a high probability (i.e. at least 67% of Monte Carlo iterations) of achieving 2050 targets. It is possible to examine a huge number of policy combinations, but I follow a particular approach, which is more illustrative than exhaustive. I model policy packages with an "Ambitious" lead policy and then test how stringent accompanying policies will need to be to have a high probability of achieving 2050 GHG reduction goal in the freight sector (i.e. 80% reduction by 2050). All policy package scenarios include the Proposed national carbon tax. I do not include scenarios with a Moderate or Ambitious carbon tax, because carbon pricing schemes typically have the highest level of opposition amongst citizens in comparison to other climate policies, and the taxation level needed for the tax to meet ambitious emissions reductions targets would likely not be politically acceptable (Mildenberg, et al, 2016; Rhodes et al, 2014). Below I present the three Ambitious lead policies with the different accompanying policies I model alongside (i.e. 23 unique policy scenarios).

Ambitious Fuel Efficiency Standards for trucks Lead Policy Scenarios:

- LCFS (Proposed, Moderate, Ambitious)
- ZEV Mandate for trucks (Weak, Moderate, Ambitious)

Ambitious LCFS Lead Policy Scenarios:

- Fuel Efficiency Standards for trucks (Current, Moderate, Ambitious)
- ZEV Mandate for trucks (Weak, Moderate, Ambitious)

Ambitious ZEV mandate for trucks Lead Policy Scenarios:

- Fuel Efficiency Standards for trucks (Current, Moderate, Ambitious)
- LCFS (Proposed, Moderate, Ambitious)

Chapter 3. Results

I present the results of my policy scenario simulations in three sections, aligning with my three research objectives. I incorporate results from the Monte Carlo Analysis in which I run 1000 iterations for each simulation to account for variations in WTW emissions from varying values of uncertain model input parameters. In Canada, climate targets (i.e. 30% by 2030 and 80% by 2050) are measured relative to 2005 levels. Thus, I use 2005 as the reference point when examining percentage changes in WTW GHG emissions.

3.1. Objective 1: Effectiveness of Canada’s current and proposed policies

For my first research objective I simulate the GHG emissions under four scenarios: i) No Policy, ii) Current (i.e. federal fuel efficiency standards for trucks), iii) Current + Tax and iv) Current + Tax + LCFS scenarios. My simulations reveal that none of these scenarios will be sufficient to achieve 2030 and 2050 GHG reductions targets (Figure 3.1). Under the most stringent scenario (Current + Tax + LCFS), the Monte Carlo Analysis reveals that less than 0.5% of iterations achieve 2030 and 2050 targets. Under the No Policy, Current and Current + Tax scenarios, emissions trend upwards, whereas under the Current + Tax + LCFS scenario, the emissions level off around 2005 levels. Thus, modeling results suggest that additional policies and/or more stringent policies will be required to achieve GHG reductions goals.

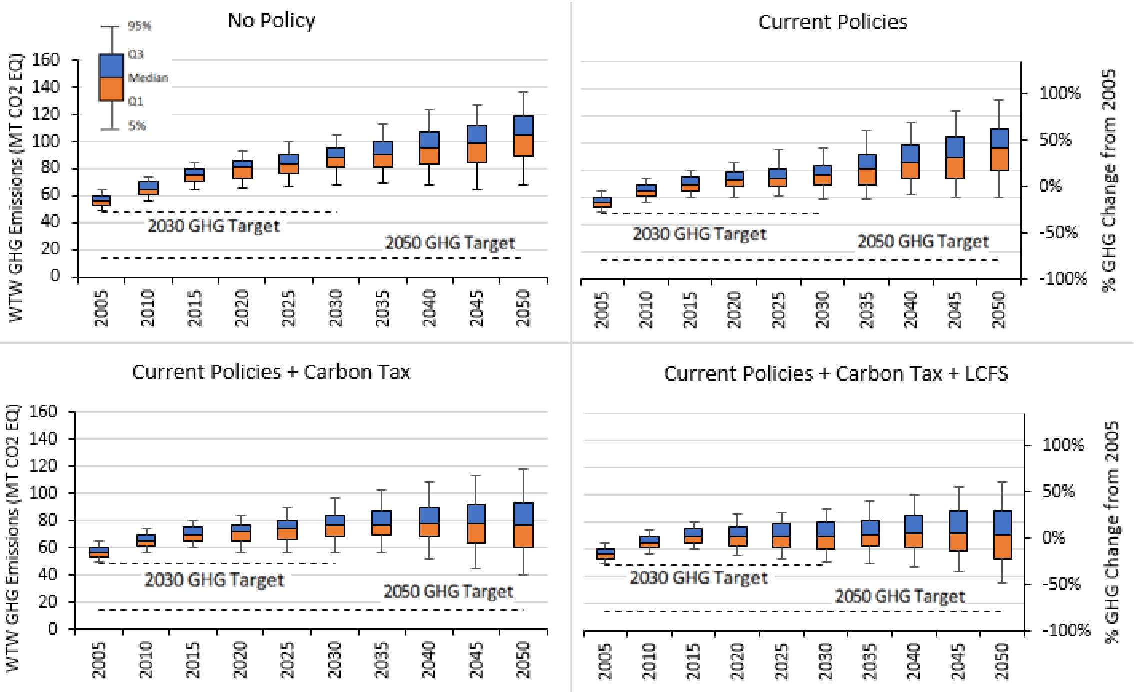

Figure 3.1. **WTW GHG emissions from Land Freight in Canada under No Policy, Current Policies, Current Policies with Carbon Tax and Current Policies with Carbon Tax & LCFS scenarios**

3.2. Objective 2: Effectiveness of individual freight policies

My second research objective is to assess the effectiveness of several individual policies in reducing freight GHG policies at different stringencies. The policies I model are fuel efficiency standards for trucks, a carbon tax, a LCFS, a ZEV mandate for trucks, and a subsidy. Each policy is modeled at three stringencies alongside the Current Policies scenario (i.e. federal fuel efficiency standards for trucks). I chose to model individual policies alongside the Current Policies scenario because proposed policies such as the carbon tax and LCFS have not been enacted and are still under development. Thus, my research could be used to help inform this development and implementation.

All modeled policies (fuel efficiency standards for trucks, carbon tax, LCFS, ZEV mandate and subsidy) serve to reduce GHG emissions relative to a “no policy” scenario, but effectiveness substantially varies across policies. I provide an overview of results from my second research objective and discuss each policy more in depth in the following sections. As I will show the ZEV mandate was the most effective policy in achieving GHG reduction in land freight. The next most effective policy was the carbon tax followed by LCFS and Fuel Efficiency Standards scenarios. Emission reduction from subsidy scenarios were relatively small in comparison to those from other policies. However, the results show that even under their Ambitious stringencies, none of these individual policies were sufficient to achieve 2030 or 2050 GHG abatement goals. This finding suggests that these individual policies will likely not be adequate to achieve reduction goals on their own at the stringencies analysed here. The inadequacy of individual policies in achieving GHG reduction goals highlights the role policy packages could play. I next provide more detail of the results for each type of individual policy.

First, for the fuel efficiency standards, it is only under the Ambitious fuel efficiency standards scenario do emission trend below 2005 levels (Figure 3.2*)*. Under the Current and Moderate fuel efficiency scenarios, emissions trend upwards compared to 2005 levels. In these scenarios, standards only serve to reduce the extent to which emissions rise through the adoption of fuel efficiency technologies. Emissions trend downwards relative to 2005 under the Ambitious fuel efficiency standards and compliance is achieved through both adoption of both fuel efficiency technology and ZEVs. However, the Ambitious fuel efficiency standards scenario achieves 2030 targets in less than 4% of simulations and 2050 targets in less than 1% of simulations, indicating that it is possible but unlikely that this scenario would reach emissions reductions targets.

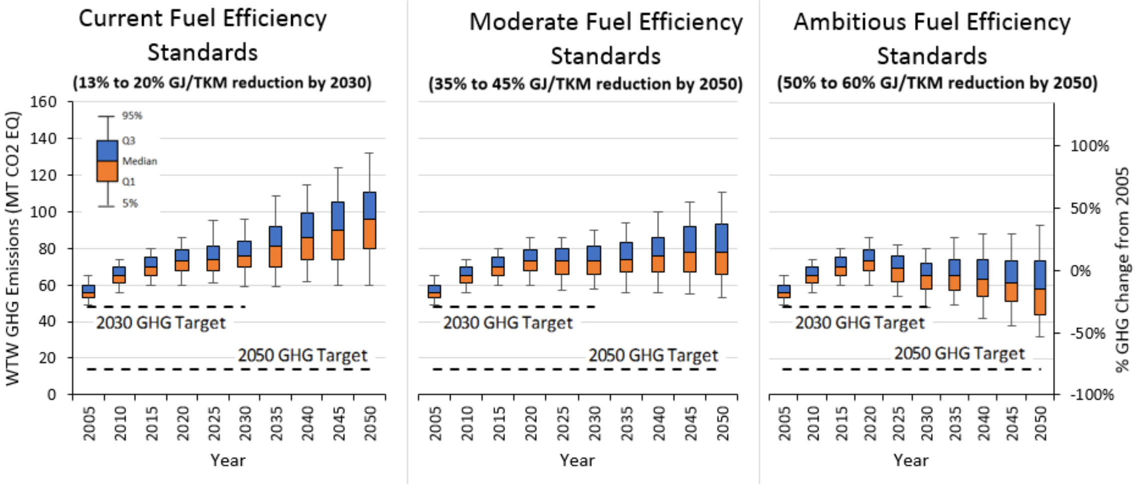

Figure 3.2 WTW GHG emissions from land freight in Canada under fuel efficiency standards scenarios (Current, Moderate, Ambitious).

Second, the carbon tax scenarios find that, under Moderate and Ambitious stringency levels, emissions trend downwards (Figure 3.3). The Proposed carbon tax achieves reductions predominately through the adoption of fuel efficiency technologies and does little to stimulate the adoption of ZEVs. Under the Moderate and Ambitious scenarios, GHG reductions are achieved through the adoption of a variety of technologies, including fuel efficiency technologies, ZEVs and alternative fuels. However, even under the Ambitious scenario, 2030 goals are achieved in less than 6% of scenarios and 2050 goals are achieved in less than 9% of scenarios, indicating that it is unlikely that these targets would be met

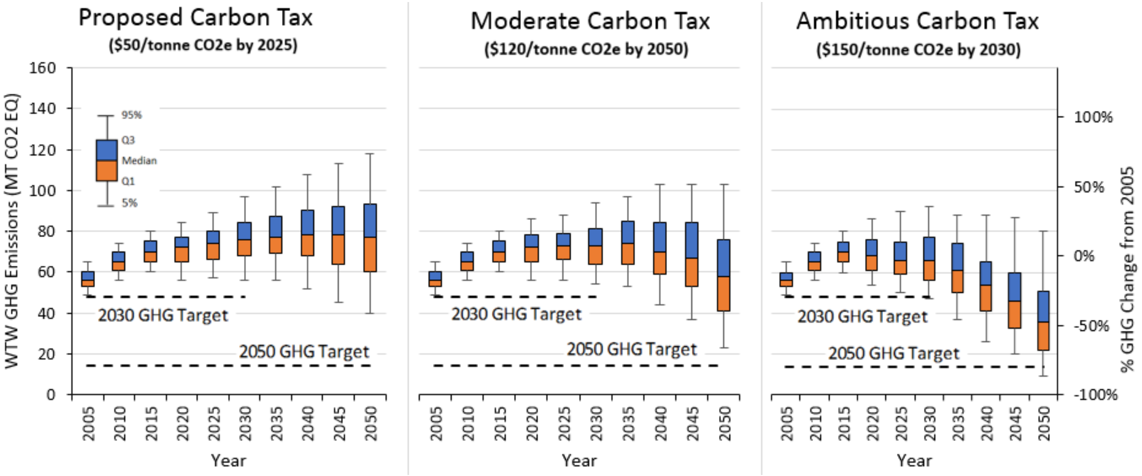

Figure 3.3 **WTW GHG emissions from land freight in Canada under carbon tax scenarios (Proposed, Moderate, Ambitious).**

Third, only under the Ambitious LCFS do emissions trend downwards (Figure 3.4). Under the Proposed LCFS scenario, GHG emissions are shown to increase relative to 2005 levels in 69% of iterations, whereas in the Moderate scenario, the trend is for emissions to level off around 2005 levels. Under the Proposed and Moderate LCFS scenarios, compliance is predominately achieved through the blending of HDRD in diesel, whereas under the Ambitious scenario, an increase in the demand for hydrogen and electricity help with achieving compliance. Under all three scenarios, GHG reductions goals are not likely to be achieved (i.e. for the Ambitious LCFS scenario less than 5% of iterations achieve 2030 goal and less than 3% of iterations achieve the 2050 goal).

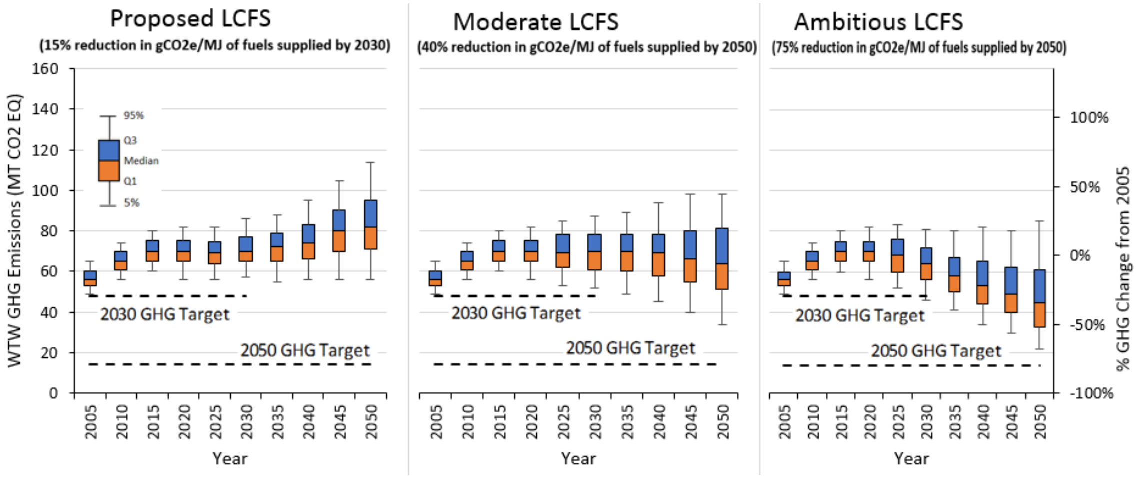

Figure 3.4 **WTW GHG emissions from land freight in Canada under LCFS scenarios (proposed, Moderate, Ambitious).**

Fourth, although unlikely to achieve climate targets, the ZEV mandate scenarios achieve the greatest emissions reductions across identified individual policies (Figure 3.5). Emissions trend downwards in all three policy stringencies as a result of the mandated adoption of ZEVs. Under the Weak and Moderate scenarios, 2030 targets are achieved in 2% and 7% of iterations respectively and 2050 targets are achieved in less than 1% and 3% of iterations respectively. Of all individual policy scenarios modeled for my second research objective, the Ambitious ZEV mandate scenario achieves 2050 in the greatest proportion of iterations (24%).

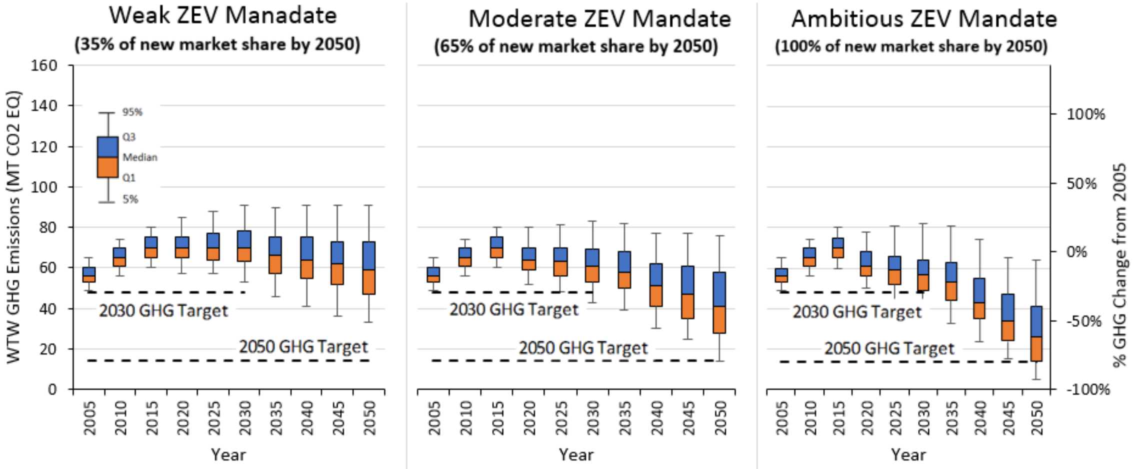

Figure 3.5 **WTW GHG emissions from land freight in Canada under ZEV mandate for trucks scenarios (Weak, Moderate, Ambitious)**

Fifth, subsidy scenarios are the least effective individual policy at reducing GHG emission (Figure 3.6), and subsidy scenarios are not sufficient to stimulate significant ZEV adoption. Increasing the subsidy stringency leads to incremental GHG reductions, but these incremental reductions are modest. GHG emissions trend upwards under all three subsidy scenarios, and less than 0.2% of iterations achieve 2030 and 2050 goals even under the Ambitious subsidy scenario.

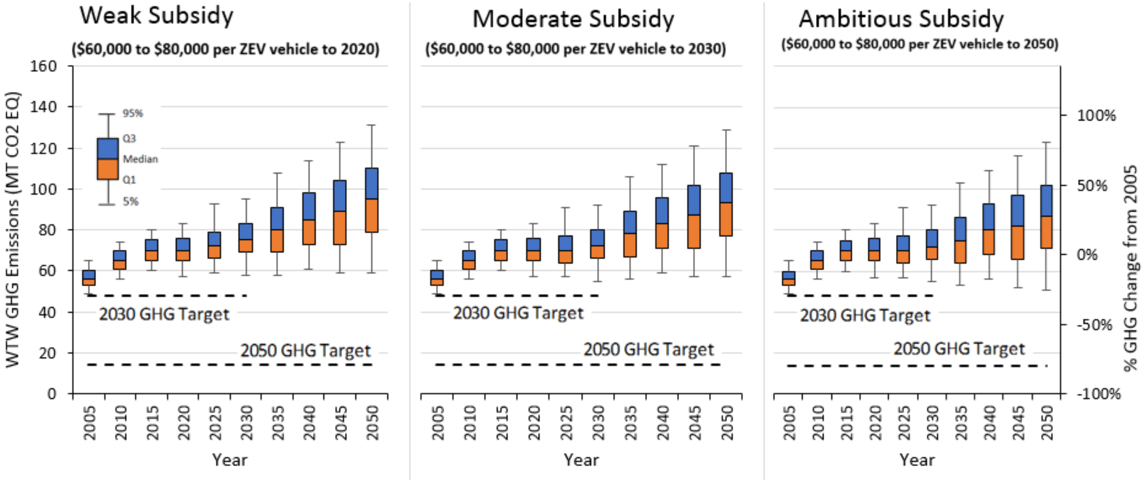

Figure 3.6 WTW GHG emissions from land freight in Canada under subsidy program scenarios (Weak, Moderate, Ambitious)

3.3. Objective 3: Effectiveness of policy combinations

Because I find that no individual policy is able to have a high probability of achieving 2030 or 2050 GHG reduction targets, my third research objective simulates policy packages. Specifically, I model policy packages with an “Ambitious” lead policy (fuel efficiency standards, LCFS or ZEV mandate for trucks), and test how stringent the accompanying policies would need to be to have a high probability of achieving 2050 GHG reduction goals in the land freight sector (80% reduction by 2050). I define high probability as scenarios that achieve 2050 GHG emission reduction goals in at least 67% of iterations. In this section, I discuss whether policies have an additive effect on the likelihood of achieving 2050 targets (i.e. an incremental impact on likelihood of achieving 2050 targets from increasing stringency).

I present results in terms of each Ambitious lead policy (see Table 3.1*)*. Under Ambitious lead policies, additional policies vary in stringency (except for the proposed carbon tax). For example, under the Ambitious fuel efficiency standards lead scenarios the stringency of the ZEV mandate and LCFS vary across stringency levels. For each scenario, the percentage of iterations that achieve 2050 targets is presented, and scenarios with a high probability of achieving the 2050 target are in bold. It is important to note that there is some overlap in policy package scenarios across lead policies (i.e. 23 unique policy scenarios). I discuss the results of scenarios for each Ambitious lead policy in the following three paragraphs and then provide an overview of my main findings across lead policy scenarios.

Under packages with an Ambitious fuel efficiency standards as the "lead" policy, two scenarios have a high probability of achieving 2050 goals. In both scenarios there is an Ambitious ZEV mandate, and the stringency of the LCFS is either Moderate or Ambitious. In all scenarios, increasing the stringency of the LCFS and ZEV mandate alongside Ambitious fuel efficiency standards has additive effects. However, increasing the stringency of the ZEV mandate has stronger additive effects on the percentage of scenarios that achieve 2050 GHG reduction goal compared to the LCFS*.*

Table 3.1 Percentage of iterations that achieve 2050 targets under "Ambitious" Fuel Efficiency Standards, LCFS & ZEV Mandate lead policy scenarios

Ambitious Fuel Efficiency Standards Lead		*ZEV Mandate*		
		Weak	*Moderate*	*Ambitious*
LCFS	*Proposed*	8%	35%	65%
	Moderate	16%	45%	74%
	Ambitious	26%	53%	85%
Ambitious LCFS Lead		*ZEV Mandate*		
		Weak	*Moderate*	*Ambitious*
Fuel Efficiency Standards	*Current*	17%	47%	85%
	Moderate	21%	50%	85%
	Ambitious	26%	53%	85%
Ambitious ZEV Mandate Lead		*LCFS*		
		Proposed	*Moderate*	*Ambitious*
Fuel Efficiency Standards	*Current*	59%	70%	85%
	Moderate	61%	72%	85%
	Ambitious	65%	74%	85%

*All scenarios include Proposed Carbon Tax

Under packages with an Ambitious LCFS "lead" policy, three scenarios have a high probability of achieving 2050 targets. As with the Ambitious fuel efficiency standards lead policy scenarios, an Ambitious ZEV mandate is part of all scenarios with a high probability of achieving 2050 reduction targets. Increasing the stringency of the ZEV mandate has significant additive effects on the percentage of scenarios that achieve 2050 goals. Increasing the stringency of fuel efficiency standards has additive effects, in terms of the percent of simulations that achieve 2050 targets, in all Ambitious LCFS lead policy scenarios except when accompanied with an Ambitious ZEV mandate. When accompanied with an Ambitious LCFS and ZEV mandate, increasing the stringency level of the fuel efficiency standards stringency does not impact percentage of scenarios that achieve 2050 goals**.**

The Ambitious ZEV mandate for trucks lead policy results in the greatest number of scenarios with a high probability of achieving the 2050 GHG reductions target. Six scenarios with an Ambitious ZEV mandate lead policy have a high probability of achieving 2050 GHG reductions targets. The three scenarios with the highest probability of achieving 2050 are accompanied with an Ambitious LCFS, whereas fuel efficiency stringency ranges from proposed to Ambitious across those scenarios. The additive effects of increasing the stringency of fuel efficiency standards decreases as the stringency of the LCFS increases, and alongside an Ambitious ZEV mandate and LCFS, increasing the stringency of fuel efficiency standards does not increase the percentage of simulations that achieve 2050 reduction goals. In contrast, a LCFS has greater additive effects than fuel efficiency standards and has additive effects even under the most stringent policy package scenarios.

In summary, consistent with my second research objective, scenarios with an Ambitious ZEV mandate lead policy have the highest probability of achieving 2050 GHG reduction targets (Table 3.1*)*. As well, all scenarios with a high probability of achieving 2050 GHG reduction targets included an Ambitious ZEV mandate. Finally, results indicate that increasing the stringency of a ZEV mandate has more additive effects on percent of iterations that achieve 2050 targets than does increasing stringency of fuel efficiency and, to a lesser degree, a LCFS. Results from policy package scenarios also reveal the additive role a LCFS can play within a package of policies.

3.4. Fuel Market Share

To better understand the impact of policy scenarios on technology uptake, I present results on the market share percentage of freight fuels per mode in 2050 under the Current policy scenario and the most stringent policy scenario I model, which includes Ambitious fuel efficiency standards, ZEV mandate and LCFS alongside the Proposed carbon tax. Figure 3.7 (Top graph) presents the median (across Monte Carlo iterations) market share of fuel technologies per mode in 2050 for the Current Policy scenario. For all three freight modes diesel fuel is the most predominant fuel type, similar to results from the no policy scenario (not shown). In the light/medium and heavy truck modes, there is some uptake of zero-tailpipe emission technologies, but fossil fuels still dominate. For rail, there is some adoption of electric and hydrogen rail, but diesel still dominates. Under the Current policy scenario, emission reductions (compared to no policy scenario) are primarily achieved through improvements to fuel efficiency of diesel technologies.

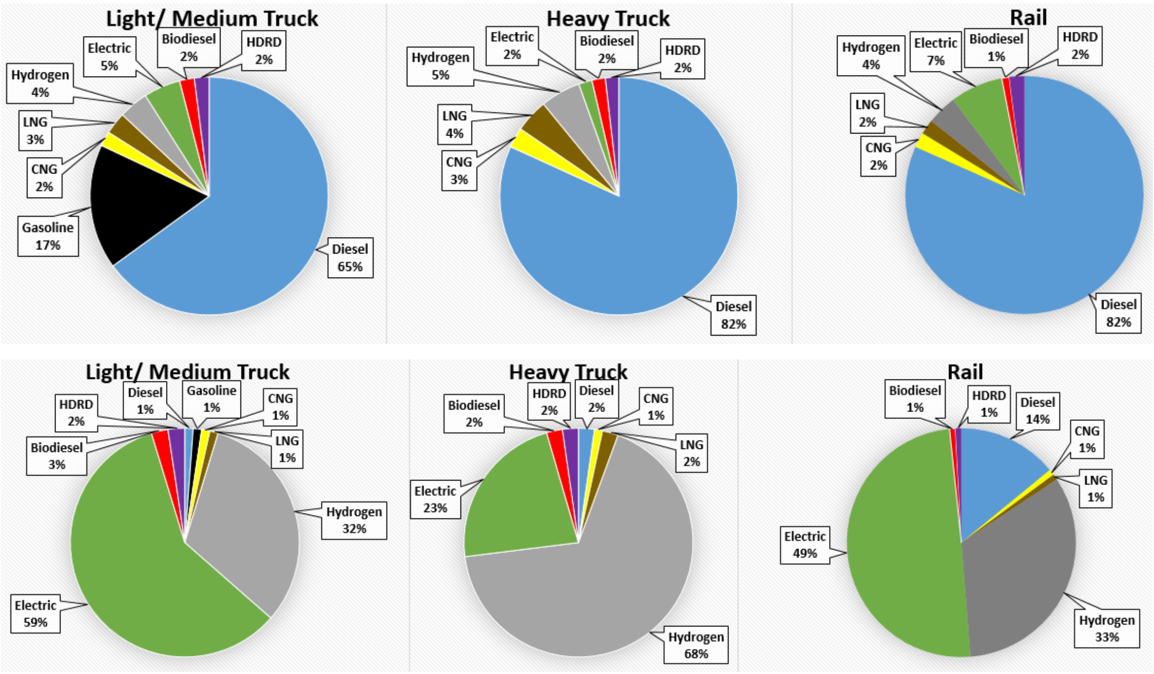

Figure 3.7 Median Market Share percentage of Fuels in 2050 under Current Policy Scenario (Top) and the Most Stringent Policy Package scenario (i.e. Ambitious fuel efficiency standards, ZEV mandate and LCFS alongside the Proposed carbon tax) (Bottom)

For comparison, Figure 3.7 (bottom graph) presents the median market share of fuel technologies per mode in 2050 under the most stringent policy scenario I model (i.e. Ambitious fuel efficiency standards, ZEV mandate and LCFS alongside the Proposed carbon tax). Under the light/medium mode, electric trucks are the most predominant technology followed by hydrogen trucks. In the heavy truck mode, hydrogen followed by electric trucks are the most predominant technologies. Finally, under the rail mode, electric technologies make up most of the market share followed by hydrogen and then diesel. Under this policy package scenario, ZEV technologies dominate the market share. This policy scenario will likely achieve 2050 GHG emission reduction targets (85% of iterations), which highlights the role ZEV technologies will likely need to play in achieving targets.

Chapter 4. Discussion and Conclusions

The goal of my research is to explore the effectiveness of policies in achieving GHG reductions in freight transportation, and to determine scenarios that could help achieve Canada's GHG reduction targets. The freight sector has been under-studied among researchers, though some studies demonstrate that without effective policies, freight emissions will continue to increase (Plumptre et al., 2017; ECCC, 2017). To date, the majority of research focusing on freight transportation has primarily used static accounting tools in which lifecycle GHG emissions are analyzed for different freight technologies to predict GHG emissions under different technical assumptions. My research helps address a gap in the literature by focusing on the effectiveness of policies and policy packages in achieving GHG reduction goals in the freight sector, specifically within the context of the Canadian federal government.

My results match the findings of other studies (ECCC, 2017; Vass, 2016; Plumptre et al., 2017) that have found current policies, even with the inclusion of the proposed carbon price and Clean Fuel Standard, will not be sufficient to achieve 2030 and 2050 GHG reduction targets. However, there is no single study that has evaluated current policies in the same packages I have used here. In Canada's Third Biennial report on Climate Change, simulations show that freight GHG emissions are predicted to increase by 15% by 2030 compared to 2005 levels under current federal policies (but not considering the proposed carbon price or LCFS). Research by Vass (2016) included a scenario with the federally proposed carbon tax (not the LCFS) and found that it helped to slow growth, but not actually decrease freight GHG emissions. All together, the research from these studies is consistent with my finding that emissions will likely remain close to 2005 levels under the proposed carbon price and LCFS.

Further, my simulations suggest that the addition of stringent individual policies alongside current policies are also unlikely to achieve 2050 climate goals. Admittedly, such goals may be possible by increasing stringency beyond what I model but I limit the stringency of each policy based on what other freight researchers have used (and what seems to be in the realm of what is politically feasible). As a similar finding, Plumptre et al. (2017) and Mccollum et al. (2009) also found there is no "Silver Bullet" policy (no single policy that will do all the work) in achieving climate goals in the freight sector.

Modeling by Vass (2016) included a scenario with an Ambitious carbon tax (rising to $200 in 2030) and, similar to my results, found that an Ambitious carbon tax on its own is not sufficient to achieve GHG reduction goals in freight. Although not sufficient to achieve reduction goals, the modeled policies could play a role in achieving reduction goals. Specifically, the ZEV mandate for trucks was found to be the most effective policy followed by the carbon tax, LCFS and Fuel Efficiency Standards and, to a lesser degree, a subsidy. However, the effectiveness of individual policies is directly influenced by stringency, which differ across policies (i.e. Ambitious ZEV mandate requires 100% new market share whereas LCFS requires 75% reduction in carbon intensity). Thus, my results align with other research indicating that it is unlikely that the implementation of a single policy will lead to the major reductions in freight emissions needed to achieve Canada's stated targets for 2030 and 2050,

Similar to Lepitzki et al. (2018) and Vass (2016), my results highlight the potential for a suite of stringent policies to reach GHG reduction goals for freight. However, the policy combinations that I found most likely to reach targets differs slightly from those used in these studies. Modelling by Lepitzki et al. (2018) found that an ambitious policy package that included a stringent ZEV mandate, carbon tax and LCFS was required to achieve 2050 GHG reduction goal (80% reduction) in British Columbia's freight sector. In contrast, I found scenarios with a Moderate LCFS, Current fuel efficiency standards and Proposed carbon that also had a high probability of achieving 2050 goals alongside an Ambitious ZEV mandate. Research by Vass (2016) found that an ambitious LCFS (reaching 80% reduction in fuel carbon intensity by 2040) and carbon tax (reaching $40 by 2030) on top of current fuel efficiency policies was required. In contrast, my results suggest that it is unlikely that this scenario would achieve 2050 reduction targets given the importance of a ZEV mandate for trucks.

My simulation results highlight the important role that a ZEV mandate can play in achieving GHG reduction goals. My modeling found that policy package scenarios with a high probability of achieving 2050 reduction targets all included an Ambitious ZEV mandate. However, my results are influenced by the fact I set the Ambitious ZEV mandate requirement to 100% of new market share of trucks. Similar to my results, modeling by Lepitzki et al. (2018) found that an ambitious ZEV mandate (i.e. requiring 100% new market share to be ZEVs) was part of the only modeled policy package (which also included ambitious fuel efficiency standards, carbon tax and LCFS) that achieved 80% reductions in British Columbia's freight sector. However, in contrast to results from Lepitzki et al. (2018), I model Ambitious ZEV mandate lead policy scenarios that require less stringent accompanying polices to have a high probability of achieving 2050 targets (i.e. Proposed carbon tax, Moderate LCFS and Current fuel efficiency standards).

Along with research by Lepitzki et al. (2018) and Vass (2016), my results illustrate that a LCFS can have an additive role (i.e. incremental impact on likelihood of achieving 2050 targets from increasing stringency) within a package of policies aimed at reducing freight GHG emissions. A LCFS was found to have additive effects in all my policy package scenarios. Lepitzki et al. (2018) found that freight seemed to particularly benefit from a LCFS because of the additive role it played within a package of policies. Specifically, Lepitzki et al. (2018) found that an ambitious LCFS was an essential part of the only scenario that achieved 80% GHG reduction goals. Research by Vass (2016) found that a LCFS reaching 80% reduction in fuel carbon intensity by 2040 was an essential policy within a package to achieve the 2050 GHG reduction goal in Canada's freight sector. In each of these studies, the 2050 freight reduction goal would not have been achieved without the inclusion of the LCFS modeled. However, in contrast to results from Vass (2016), I found that without an Ambitious ZEV mandate 2050 targets would not be achieved even with an Ambitious LCFS.

4.1. Policy Implications

In this section, I discuss the policy implication of my results for the Canadian Federal Government, although my results are likely applicable to other governments with the jurisdiction to enact simulated policies (i.e. provincial/state governments, USA Federal Government). The Government of Canada has set ambitious reduction targets (30% by 2030 and 80% by 2050 relative to 2005 levels) and reducing freight emissions will likely need to play a role in achieving these goals (ECCC, 2017). I present my results in the context of achieving an 80% reduction in freight GHG emissions by 2050 relative to 2005. However, in reality the GHG targets are economy wide, and it is possible to still achieve targets without an 80% reduction in freight by 2050 if there are significant decreases in other sectors.

According to my simulations, a suite of policies that includes the current policies (i.e. fuel efficiency standards) and proposed policies (i.e. carbon price and clean fuel standard) is not strong enough to achieve GHG reduction goals and emissions will likely not decrease below 2005 levels. Although not sufficient to achieve GHG reduction goals, all three of these policies can play a role in reducing freight GHG emissions. As such, the implementation of a federal carbon tax and LCFS is a step in the right direction towards addressing freight emissions, but the stringency of these policies will need to be increased or additional policies will need to be implemented in order to achieve any significant freight GHG reductions.

Transitioning to ZEVs will likely play an important role in achieving GHG reduction goalsin freight (Moultak et al., 2017; Fulton et al., 2015; de Doer et al., 2013). As such, compulsory policies that drive ZEV uptake, like a ZEV mandate, can be a particularly useful policy tool for the federal government to achieve GHG reduction goals in freight. My results illustrate the important role a ZEV mandate can play within a package of policies. In fact, all policy scenarios with a high probability of achieving 2050 targets included an Ambitious ZEV mandate. The implementation of a ZEV mandate demonstrates a commitment to transitioning to ZEVs and is a targeted way to ensure ZEV development and commercialization (Fulton et al., 2015).

A LCFS can be particularly useful policy within a package of policies. My results illustrate the additive effect a LCFS can have alongside a package of policies. In fact, I found that policy packages with a high probability of achieving 2050 reduction goals required at least a Moderate LCFS. Whereas fuel efficiency standards and ZEV mandates achieve emission reductions by improving vehicle technologies, a LCFS achieves emission reductions through reducing the carbon intensity of supplied fuels. Policies targeting both ZEV uptake and the production low carbon fuels will likely be needed to achieve significant emissions reductions in freight in terms of WTW emissions (Fulton et al., 2015; Lepitzki et al., 2018), and a LCFS can help ensure the supply low carbon fuels.

4.2. Limitations and future research

The results of my study are dependent on the assumptions I made regarding the technological development of freight vehicles and fuels as well as consumer preferences during simulation periods. Although I base my vehicle and fuel technological parameters on literature, the actual trajectory of future technological development from now until 2050 is unknowable. Currently, few ZEV freight technologies are commercially available, and as they progress, their development could take several paths. As well, technologies not included in my model (i.e. catenary wire trucks) could emerge and play a role in decarbonization of freight. Along with vehicle technologies, the advancement and availability of low carbon fuels is uncertain, and variations in technological development could influence pathways to achieving GHG reduction goals. Finally, predicting how consumers will respond to emerging vehicle technologies and fuels is uncertain and varying preferences could influence future progression.

My modeling has several limitations stemming from model design and assumptions, which could influence modeling output. Below I discuss, these limitations and how future research can build upon my results to help address these limitations.

- My model does not incorporate an endogenous representation of the fuel supply sector, nor does it account for supply constrains or interactions between the fuel and freight sectors. I use exogenously set fuel prices and carbon intensities to capture fuel trajectories until 2050. As a result, fuel prices do not change in response to changes in their demand. As well, by setting carbon intensities exogenously, I restrict the ability of fuel suppliers to reduce production emissions to comply under LCFS scenarios. I include carbon intensity and fuel prices as an uncertain model parameter into my Monte Carlo Analysis to capture variations in their values, but future research could benefit from incorporating an endogenous representation of the fuel supply sector.

- Output per mode is exogenously set in my model based on historical and simulated trends, which restricts changes in choice of freight transport mode. Research has identified a modal switch, specifically from trucking to rail, as a possible GHG mitigation strategy (Plumptre et al., 2017; Nealer et al., 2012). However, current trends indicate that Canada is experiencing a modal shift to trucking (ECCC, 2017; Natural Resource Canada, 2012). The current trends are captured in projected output growth per mode. However, policy could help reverse this trend, and CIMS-Freight does not capture the potential impacts from a modal switch away from trucking. Future research could allow for some endogenous modal switch between trucking and rail by including capital and intangible costs to account for decision factors when choosing between these modes. Research by Vass (2016) includes modal switch between trucking and rail, which is a good reference for future research.

- My model does not differentiate between heavy truck long-haul and short-haul. Research by Moultak et al. (2017), Fulton et al., 2015 and de Doer et al. (2013) suggests that ZEV trucks face different adoption barriers depending on their application. Short-haul heavy trucks, including drayage trucks, travel shorter daily distances, and as a result are less impacted by limited range and longer refuel times associated with battery electric trucks. As well, short-haul trucks that use high freight use routes may be a potential candidate for overhead catenary wires (Moultak et al., 2017). Future research could benefit from splitting the heavy truck mode into short-haul and long-haul heavy trucks and adjusting intangible costs to reflect differences between the two.

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