Assessing Uncertainties of our Climate-Friendly Road Freight Options

by

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Abstract

To reduce greenhouse gas emissions and mitigate climate change, all sectors of an economy must be addressed. Some sectors seem to have a clear path on the road to zero-GHG emissions, but other sectors, like road freight, remain unclear. Few have attempted to reduce emissions in road freight due to relatively high costs and considerable uncertainty about likely technology and energy pathways. This study will apply scenario analysis to forecast potential zero-emission pathways in the road freight sector by assessing how key uncertainties may affect the likely contributions of zero-emission hydrogen, electric, and flex-fuel biodiesel trucks to the road freight sector. CIMS, a partial equilibrium energy-economy-emissions model, is used to provide insight into possible market shares, greenhouse gas emissions, and life-cycle cost of zero-emission truck options for a variety of different zero-emission pathways based on uncertain parameters.

Keywords: Uncertainty; Road freight sector; Heavy-duty truck; Sensitivity analysis; Life-cycle costs; Climate change

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List of Acronyms

AEEI	Autonomous Energy Efficiency Index
BAU	Business-as-Usual
BEV	Battery Electric Vehicle
BTL	Biomass-to-Liquid
CCS	Carbon Capture and Storage
CIMS	Canadian Integrated Modeling System
EIA	Energy Information Administration
FAME	Fatty Acid Methyl Esters
GHG	Greenhouse Gas
GTL	Gas-to-Liquid
HEV	Hybrid Electric Vehicle
HDV	Heavy-Duty Vehicle
HVO	Hydro Treated Vegetable Oils
LCC	Life Cycle Cost
PHEV	Plug-in Hybrid Vehicle
SMR	Steam Methane Reforming
tCO_ze	Tonne Carbon Dioxide Equivalents
TKT	Tonne Kilometer Traveled

Chapter 1. Introduction

Governments around the world are agreed on the urgent need to reduce greenhouse gas (GHG) emissions to zero. Due to technological breakthroughs and rapid cost declines, the likely zero-emission pathway appears to be fairly clear in some sectors, such as personal transportation and electricity. However, in others, there is a great deal of uncertainty. Road transport of freight is one such sector.

One reason the zero-emission pathway for road freight remains unclear is that most governments agree on the need for urgent action, but few have taken steps to actually curb the use of fossil-fuels in large trucks. As a result of governmental inaction, diesel and, to a lesser extent, gasoline trucks remain the cheapest truck options, allowing them to dominate the market (International Energy Agency, 2019a).[1] This situation is unlikely to change until strong policies are implemented that put a significant charge on GHG emissions and/or regulate technologies and fuels.

Currently, many governments are considering, and in some cases gradually implementing, policies to regulate and price emissions from all fossil-fuel using technologies, including freight trucks. If these policies are technology- and energy-neutral, research literature suggests that three technology-energy options have a significant chance of playing a key role for road freight: hydrogen, electricity, and biodiesel. However, for several reasons there is considerable uncertainty about which of these is likely to dominate a low-GHG road freight future.

First, zero-emission technologies may have uncertainties about the cost evolution of the vehicle, its fuel, or the infrastructure needed for operation. Hydrogen and electric trucks, for instance, face multiple uncertainties. The dominance of diesel trucking has limited research into the development and production scale-up of these technologies. As a result, hydrogen and electric trucks are operational, but further advancements are necessary for them to become comparable to diesel trucks in terms of costs, payload capacity, range, and refueling time. For example, few experts can agree on the current or future costs of zero-emissions trucks, given that so few of these types of trucks are currently used for road freight transport. Estimates from literature suggest that hydrogen

[1] Intra-city utility trucks are fueled by gasoline in the road freight sector.

trucks could be anywhere from 90% to 260% more expensive than diesel trucks, depending on truck type (den Boer et al., 2013; Fulton & Miller, 2015; Meszler et al., 2015; Moultak et al., 2017; Navius Research, 2020). Costs for hydrogen fuel production and delivery infrastructure also remain high currently and uncertain in future because without strong climate policy there is little incentive to develop them for use in transportation.

Eventual costs for electric trucks, their fuel, and infrastructure are also uncertain. For example, estimates from the research literature suggest that electric trucks may cost 90% to 220% more than conventional diesel trucks (den Boer et al., 2013; Meszler et al., 2015; Moultak et al., 2017; Navius Research, 2020). Electric trucks may, however, have an advantage over hydrogen options due to lessons learned with personal and public transportation vehicles. For example, the 2020 survey of transit vehicles in California indicated that approximately 15% of buses were electric powered (National Transit Database, 2020a, 2020b). Operators are comfortable using electric buses because routes and schedules are well-established, making it easier to know when and where to recharge batteries. As the electric fleet grows in the personal transportation sector, advancements occur to improve batteries, motors, and infrastructure which may spillover to reduce costs for electric trucks used for road freight, as innovations in one sector benefit the other.

Biodiesel trucks (also known as flex-fuel trucks), on the other hand, are more expensive than diesel trucks, but because of similar drivetrains their costs are relatively close and thus less uncertain in future. Biodiesel trucks in the road freight sector can run on conventional biodiesel, renewable diesel, or regular fossil fuel-derived diesel to varying degrees. Biodiesel is already part of the transportation landscape, potentially giving biodiesel trucks an advantage over other technology options. A 2017 report from Sweden indicated that the policy combination in that country of a carbon price, biofuel blend mandate, and vehicle emission regulation has resulted in 21% of transportation already powered by biofuels (The Swedish Transport Administration, 2017). In California, a variety of climate policies has increased the use of biodiesel in conventional diesel trucks to 13.7% in 2017 from 0.4% in 2011 (Witcover, 2018). In jurisdictions where biodiesel is replacing fossil fuel diesel in existing trucks, technological blending limits become an important constraint. These barriers can be overcome if conventional engines are modified, more flex-fuel trucks are available, or renewable diesel replaces traditional biodiesel. Renewable diesel has the same chemical properties as diesel, yet it is considered zero-emission because it is made from organic matter. Each of these technological solutions to overcome blend limits results in higher costs than current trucks and fuels, which prevents these solutions from becoming competitive in the market if climate policies are weak. Biodiesel costs are also uncertain due to concerns about the use of food crops for production especially as production increases to levels that may cause higher costs for land that may also be in demand for food production, fibre production and biodiversity conservation. If concern mounts, second- and third-generation biodiesel can be produced from organic wastes, residues, or algae. Biodiesels from these sources may not currently conflict with food production, but production methods are in early-development stages, so costs are uncertain and unforeseen drawbacks could arise as production increases.

The second reason the zero-emission pathway for road freight is uncertain is that it is a diverse sector. It includes seven vehicle classes that range from large pick-ups to semi-trucks. Trucks can be driven within a single city or across regions. Some trucks drive the same route each day, while others have variable routes, depending on their purpose. As a result, each of these types of trucks is constructed differently, resulting in different capital and fuel costs and this means that some types of trucks may be better suited than others for some zero-emission fuels. For instance, trucks that drive the same route each day may be suited to electrical powertrains and battery storage, while long-haul trucks may have better economics for liquid and gaseous fuels that store more energy and thus provide longer ranges. Moreover, trucks that travel further distances require greater use of infrastructure to meet refueling needs, and, thus, have greater costs than trucks used for shorter trips. This diversity in the road freight sector contributes to the uncertainty of the zero-emission pathway because some technology options might do competitively better for one type of truck, but worse for another.

The third reason for uncertainty in the pathway to zero-emission road freight in Canada is that the outcome in one jurisdiction will depend on its policy, but also on policies elsewhere. When the world works together to mitigate climate change, costs for zero-emission technologies are likely to fall faster than when only a few countries act. This is because global mitigation may result in faster rates of economies-of-scale in production and economies-of-learning in operation, thus lowering costs of zero-emission technologies at a faster rate. The amount of global mitigation effort may also influence the price of oil. If major emitting countries are seriously reducing their GHG emissions, the price of oil may fall as its demand decreases. On the other hand, if substantial climate effort is only made by a sub-set of countries with less consequence for global markets, the demand for oil and thus its price may remain high. Thus, the rate of zero-emission technology cost declines and the future price of oil are both dependent on the level of global mitigation effort. Yet, the level of that effort is highly uncertain, influenced as it is by the priorities of governments, societal pressure, and political and economic developments that are often difficult to anticipate.

In this study, I explore these uncertainties. I do so by asking the question, “what are the likely contributions of each zero-emission technology to a near-zero GHG emission road freight sector given different assumptions about global GHG mitigation efforts and technological parameters?” To address this question, I have three objectives:

1) Disaggregate on-road trucks to assess how road transport service heterogeneity influences which trucks may have better prospects on the zero-emission pathway.

2) Identify the zero-emission technologies that could replace conventional diesel and estimate the range of uncertainty for the cost of the vehicles themselves, the fuels they require, and the infrastructure they need.

3) Explore and analyze using sensitivity analysis how changes in the value of the key uncertain technological variables may influence forecasts of the future market shares of each competing option as Canada pursues GHG reduction throughout its economy.

For my first objective, I disaggregated the road freight sector into three vehicle “modes” – “Light-Medium Motors” to represent light vehicles that travel within a city, “Short-Haul Heavy Motors” that travel within a city, and “Long-Haul Heavy Motors” that represent heavy vehicles that travel regionally. I thus established 26 distinct vehicle technologies that would enable me to estimate which type of zero-emission truck might dominate in each vehicle mode.

For my second objective, I conducted a literature review of zero-emission trucks, their fuels, and their infrastructure and from this updated the reference cost estimates used in the CIMS energy-economy-emissions model to estimate future market shares of competing technologies. I also established a range of uncertainty in costs for each of these variables. For most values, the range of uncertainty was limited to a cheap and a baseline simulation, while for some I included an additional expensive simulation.

Using these uncertainty ranges, I developed 26 simulations – each representing either a cheap, baseline, or expensive cost for technological parameters and different levels of mitigation effort to assess how the key uncertain values may influence the pathway to a zero-GHG emission road freight. I modeled the road freight sector from 2020 to 2050 for each simulation, resulting in 26 forecasts of “New Market Share” to achieve my third research objective. These results provide insight on New Market Share sensitivity to uncertain technological parameters and the level of global mitigation efforts.

In Chapter 2, I provide background information on Canada’s road freight sector and the available zero-emission technologies and energy options. In Chapter 3, I explain the methodology and main assumptions I used in this study, including the CIMS model, the disaggregation of the road freight sector, updates to the CIMS model for zero-emission technologies, and an overview of the scenarios and simulations I ran to assess how uncertainties in technological parameters and climate mitigation efforts might affect new market shares. In Chapter 4, I discuss the results. Finally, in Chapter 5, I summarize the main findings and briefly discuss limitations and future research.

Chapter 2. Background

In this chapter, I contextualize the road freight sector in Canada. I begin by describing the road freight sector, in terms of truck size and haul type. Next, I summarize the strategies that can be used to reduce GHG emissions in the road freight sector. Finally, I summarize the zero-emission truck options, as well as discussing the opportunities and challenges that exist for each truck type.

2.1. Types of Road Freight Trucks in Canada

In Canada, there are nine vehicle weight classes; seven of those classes can be disaggregated into road freight trucks. Class 1 and 2a consist of personal transportation vehicles, so they are not considered within this study. Class 2b and 3 are designated as light-heavy duty trucks, weighing between 8,500 and 14,000 pounds (Environment and Climate Change Canada, 2021b). These range from full-size pick-ups (e.g., Ford-250) to small walk-in trucks, such as doorless postal trucks. Light-heavy duty trucks are short haul which means they are typically driven within a region, often within a single city, averaging 150 to 400 kilometers daily. Light-heavy duty trucks comprise 64% of the Canadian road freight sector (Natural Resources Canada, 2020).

Class 4, 5, and 6 are designated as medium-heavy duty trucks, ranging from 14,000 to 26,000 pounds. Delivery trucks, bucket trucks (commonly used for repairing telephone wires), and larger walk-in trucks (e.g., food trucks) are within this class. Medium-heavy duty trucks typically remain within a single city and drive fewer kilometers each day, thus referred to as short-haul. Medium-heavy duty accounts for 30% of freight trucks in Canada (Natural Resources Canada, 2020, p. 60).

Heavy-heavy duty trucks weigh over 26,000 pounds and include Class 7 and 8. Class 7 are shorter haul, such as street sweepers and garbage trucks (Fulton & Miller, 2015). Because of shorter hauls, Class 7 trucks may be less impacted by the limited range and longer refueling times of some zero-emission truck options. Class 8 includes the largest delivery (such as furniture delivery), semi, and cement trucks. But most class 8 trucks are used for longer haul, travelling up to 1,500 km daily, typically between regions, and countries. Heavy-heavy duty trucks account for 6.7% of the road freight sector (Natural Resources Canada, 2020)

To reduce GHG emissions in road freight, each truck class must be considered. Given the range of truck type, sizes, and haul-type, it is possible that each class may achieve zero-emission at different rates and using different low-emission technologies.

2.2. Options for Reducing GHG Emissions in Road Freight

To reduce GHG emissions from the road freight sector, there are four approaches: (1) reduce road freight demand, (2) improve truck energy efficiency if burning oil products, (3) mode shift from road freight to an alternative such as rail, and (4) fuel switch away from oil products to a zero-emission energy option like electricity, hydrogen, or biodiesel.

Past trends suggest that it will be difficult to lower demand for road freight. From 1990 to 2016, freight truck demand increased 128% (Natural Resources Canada, 2016). Consequently, road freight GHG emissions increased 153% from 1990 to 2019 (Environment and Climate Change Canada, 2021a). Estimates suggest that without stronger climate policy, emissions from the road freight sector may increase 15% from 2015 to 2030 in Canada (Government of Canada, 2017). Demand for freight trucks has increased because of GDP growth, population growth, and the transition to e-commerce shopping and it would be difficult to reverse these trends in an attempt to reduce road freight demand (Carrara & Longden, 2017; West et al., 2012).

The second approach to reduce GHG emissions in road freight is to improve the energy efficiency of existing trucks that run on oil products. Energy efficiency is a measurement of how much energy a vehicle uses per kilometer. Typically, the heavier the vehicle, the more inefficient it will be. For example, the average efficiency for passenger cars in Canada is 8.7 liters of diesel per 100 km (Natural Resources Canada, 2020). Heavy duty trucks, on the other hand, use 29.9 liters of diesel per 100 km (Natural Resources Canada, 2020). In Canada, heavy duty vehicle efficiency regulations improved energy efficiency 31% from 1990 to 2013 (Natural Resources Canada, 2016). However, improving energy efficiency can result in the ‘rebound effect’ (Greening et al., 2000). The rebound effect occurs when efficiency improvements reduce operating costs, so energy-consuming trucks become less expensive to run and firms may find it profitable to use them more often. As a result, efficiency regulations that are meant to reduce fuel use may cause less of a reduction than anticipated.

The third option to reduce GHG emissions from road freight is to switch modes, likely trucks to rail. Rail transportation of freight is environmentally beneficial as diesel trains use less energy than diesel trucks per tonne-kilometer transported, but past trends suggest that firms favor trucking over rail regardless of efficiency. From 1990 to 2016, truck transport of freight increased 128%, while rail transport increased only 51% (Natural Resources Canada, 2016). Trucks are favored over trains in some cases because of their greater flexibility: truckers can drive where and when they want with few restrictions. Trains are restricted to rail lines and follow strict schedules, thus restricting the movement of goods. The transition to rail requires strong mode shifting policy, but few governments seem willing to implement anything that would restrict the movement of goods.

The fourth option to reduce GHG emissions from the road freight sector is to fuel switch away from trucks that burn oil products. Fuel switching reduces emissions by replacing oil-consuming technologies, mostly diesel-burning trucks, with zero-emission end-use technologies, namely trucks powered by hydrogen, electricity, or biodiesel. In Canada, this type of fuel switching has mostly occurred in the personal transportation sector with zero-emission vehicles reaching 5.2% of light-duty vehicle sales in 2020 (Statistics Canada, 2021a). Fuel switching can also occur by blending biodiesel into oil-derived diesel. In conventional diesel trucks, this form of fuel switching is currently limited to 20% without causing harm to a conventional engine. But forms of biodiesel are under development that can completely replace conventional diesel in a conventional truck. Conversely, a truck can be purpose-built to use a high blend of biodiesel – what is sometimes referred to as a flex-fuel vehicle. In Canada, biodiesel use in transportation has increased slightly, accounting for approximately 3% of the volume of blended diesel fuel (Navius Research, 2021).

Compared to some countries, Canada is behind when it comes to fuel switching. In Sweden, for instance, 8% of new truck sales in 2018 were electric and 1.4% were flex-fuel (The Swedish Policy Council, 2019; Trafik Analys, 2019), and, in 2017, 22% of energy used in transportation came from biofuels, mostly biodiesel (The Swedish Policy

Council, 2019). Sweden has achieved fuel switching due to strong climate policies, including a carbon price set to €114 per tonne CO_2 in 2021 and a biofuel blend mandate set to 21% in 2020 (International Energy Agency, 2022; The Swedish Policy Council, 2019). As a result of these fuel-switching policies, transportation emissions in 2019 were 20% below 2000 levels.

2.3. Zero-Emission Technologies

Each of the three zero-emission road truck options poses specific opportunities and challenges.

2.3.1. Hydrogen Trucks

To keep the study simple, I assume that all potential hydrogen trucks would be powered by a fuel-cell, thus requiring a hydrogen storage tank and an electric motor. Within the fuel-cell, a chemical reaction occurs between hydrogen and oxygen to power an electric motor. The by-product of this process is water that is released through a tailpipe, resulting in zero tailpipe GHG emissions. Hydrogen trucks are considered a promising alternative to conventional diesel trucks because they can travel long distances, have rapid refueling times, and have better energy efficiency than diesel. A typical diesel truck can travel 1,100 km before it needs to refuel and pilot projects find that hydrogen trucks can travel the same distance (Transport and Environment, 2020). A conventional diesel truck needs three minutes to refuel while hydrogen trucks need three to 20 minutes, depending on size (Transport and Environment, 2020). This is not a concerning discrepancy for truck operators and refueling time is consistently improving (den Boer et al., 2013). Hydrogen trucks are fuel-efficient, converting approximately 60% of hydrogen into usable energy compared to diesel trucks which have maximum efficiencies between 37% and 39% (Chandler et al., 2016; Thiruvengadam et al., 2014).

Unfortunately, there are challenges associated with hydrogen trucks. First, hydrogen fuel has uncertain and potentially high production costs. The dominant method of hydrogen production is steam methane reforming (SMR), but this method produces GHG emissions. Steam methane reforming with carbon capture and storage (SMR with CCS) is an alternative production method that produces far fewer emissions, but it is 10% to 75% more expensive than SMR due to the costs of properly storing carbon which depends on production location, transportation costs, and quality of underground storage (International Energy Agency, 2020; Kayfeci et al., 2019).[2] Electrolysis is another potentially zero-emission method of producing hydrogen.[3] Hydrogen via electrolysis is 100% to 1000% more expensive than hydrogen produced via steam reforming, and this high range is due to the divergent costs of producing zero-emission electricity (Kayfeci et al., 2019). Without strong climate policies affecting the choice of hydrogen production method, none of the alternatives can compete with steam methane reforming combined with CO_2 venting to the atmosphere. But I do not consider this option, as it makes little sense to reduce end-use emissions from trucking by using forms of energy that produce high emissions in production. I assume, therefore, that the hydrogen for trucks is produced either by electrolysis using zero emission electricity or by steam methane reforming with carbon capture and storage. Both of these can, with enough uptake in Canada or elsewhere, eventually benefit from economies-of-scale and economies-of-learning to reduce the costs of producing zero-emission hydrogen for fuel cell powered trucks and other end-use technologies.

Hydrogen fuel cell trucks are currently more expensive than conventional diesel trucks because they require specialized equipment at specific sizes to deliver the same range as diesel trucks. Hydrogen trucks require fuel tanks that can safely store sufficient compressed hydrogen and fuel cells that can properly convert the hydrogen into usable energy. These specialized components are responsible for over 60% of the capital cost of each truck and result in costs that are currently estimated at 90% to 260% more than diesel trucks, depending on truck type (den Boer et al., 2013; Fulton & Miller, 2015; Meszler et al., 2015; Moultak et al., 2017; Navius Research, 2020; Sharpe & Basma, 2022)

To refuel, hydrogen trucks require specialized infrastructure. Hydrogen refueling stations operate like existing diesel stations with the fuel stored in a tank attached to a pump and nozzle to inject the fuel into a truck. Hydrogen stations require pressurized storage tanks. Some refueling stations produce hydrogen onsite via a small-scale reformer or electrolyzer, others require a hydrogen distribution network to deliver hydrogen to the

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[2] SMR with CCS uses natural gas to generate steam. Methane is added to the steam to create a mixture of synthetic gases. Then hydrogen is isolated from the other gases. The methane is captured and stored underground to complete the process.

[3] Electrolysis uses electricity to split water into hydrogen and oxygen. Electrolysis that uses renewable energy to produce electricity produce zero-emissions.

station via pipeline or truck. Currently in Canada, few hydrogen refueling stations exist – an obvious barrier to hydrogen truck adoption (den Boer et al., 2013). The capital cost of each station is dependent on where the hydrogen is produced, the cost of the station's storage tank, the size of the storage system, and the level of pressurization.

2.3.2. Electric Trucks

In this study, fully electric trucks include battery electric (BEV) and catenary trucks, while trucks plug-in hybrid (PHEV) trucks are partially electric. Each type of truck has opportunities and challenges.

Battery electric trucks produce zero tail pipe emissions because they are fully electric. They are also three to four times more energy efficient than diesel trucks and typically have lower annual maintenance costs because they require fewer moving parts to operate and do not need oil changes. The barriers to electric truck adoption include the high capital cost of the trucks, range anxiety, slow refueling time, and the lack of a recharging infrastructure network for road freight. Currently, electric trucks can travel only about 250 km before needing to recharge their batteries (Tevva, 2021). Range improvements require advances in battery technology. Currently, batteries that offer adequate driving ranges are too large and heavy, which reduces payload capacity and is thus a major challenge in an industry in which payment is often based on the weight of cargo. Of all the zero-emission trucks available, electric trucks require the most time to refuel, often recharging for eight hours or more which is problematic for operators who want their trucks on the road and earning profit. To complete trips, BEVs will likely need depot chargers and on-road rapid chargers along road networks. Depot chargers enable recharging when trucks are not in use, typically but not always at night. Depot chargers for freight trucks are similar to existing charging stations for personal vehicles, so they can be considered near a mature commercial scale. High-speed chargers are under development to speed up recharging along the road network, but they are expensive, and few have been installed for commercial use. Batteries are the most expensive component of BEVs, representing up to 60% of the truck's upfront cost (Sharpe & Basma, 2022). As a result of high battery costs, electric trucks cost 90% to 220% more than conventional diesel trucks (den Boer et al., 2013; Meszler et al., 2015; Moultak et al., 2017; Navius Research, 2020).

Catenary trucks operate like trolleys. The vehicle connects to overhead wires which provide power to a battery and electric motor on board. Because of the constant flow of energy to the truck while connected to the wires, the range of catenary trucks is limited only by the overhead wire network, not by recharging time. Catenary wires could be installed on key road freight corridors to enable inter-city truck travel. Catenary trucks can disconnect from the wires once they have approached city-centers, so they can deliver their goods while powered by the fully charged battery, just as trolley buses can disconnect from their wires for shorter travel. Thus, I assumed in this study that each truck could be powered by a battery when not attached to the catenary wires. Catenary trucks are cheaper than BEVs because the battery they require is significantly smaller, but they are still approximately 55% to 80% more expensive than diesel trucks (den Boer et al., 2013; Moultak et al., 2017). The largest barrier to catenary truck adoption is the cost of installing and maintaining catenary networks on freeways.

Hybrid trucks are powered by an internal combustion engine that uses diesel paired with an electric motor which uses energy stored in batteries. The battery onboard is recharged through regenerative braking and the internal combustion engine. Hybrid trucks have fewer GHG emissions than diesel trucks due to the assistance of the electric motor, but always require diesel to power the motor, so I do not include them as a zero-emission vehicle. Plug-in hybrid vehicles are also equipped with an internal combustion engine and an electric motor, so they are excluded as these too would combust diesel when the battery needed recharging while during trips. In future research, however, this exclusion might be revisited. PHEVs may be a viable near-zero-emission option for trucks used within cities if their typical daily use usually does not exceed the battery's capacity.

From an energy system viewpoint, for an electric truck to be considered zero-emission, the electricity generated to power it must be produced using zero-emission methods. In Canada, 80% of current generation relies on renewable energy (Canada Energy Regulator, 2019). Electricity production and delivery costs are more certain than those of hydrogen or biodiesel in Canada because zero-emission production methods are well-established and in-use. Regardless, future costs can be influenced by changes in demand or production methods, resulting in a small range of uncertainty.

2.3.3. Biodiesel Trucks

Biodiesel trucks are powered by diesel made from biomass, which is organic matter that can be converted into a secondary energy source. Biodiesel is considered a zero-emission fuel because biomass feedstocks, which absorb carbon while growing, offset GHG emissions when biofuel is burned, resulting in a net-zero balance of GHG emissions (Alleman et al., 2016). Biomass fuels are sometimes categorized into three generations to disaggregate between biomass feedstock types. First-generation is edible organic feedstock (e.g. corn, soybean, palm). Second-generation is inedible organic feedstock (e.g., forest and crop residue, used cooking oils). Third-generation is made from microorganisms such as algae.

Once a feedstock has been harvested, different production methods can be applied to convert biomass into traditional biodiesel or renewable diesel. Traditional biodiesel is typically produced via first-generation feedstocks like vegetable oils (e.g., palm, rapeseed, soybean) or animal fats and sugars (Rauch et al., 2013). Fatty acid methyl ester (FAME) is a first-generation, conventional biodiesel produced via transesterification and can be blended with diesel up to 20% in existing trucks (Tuli & Kasture, 2022).[4] Recently, the term "renewable diesel" has been invented to refer to biodiesel that can be blended to far higher levels, perhaps even 100%. For this paper, my use of the term biodiesel includes both types of diesels made from biomass.

Renewable diesel can be produced from various sources and processes, a prominent one being hydrogenation-derived renewable diesel (HDRD), a key process of which is hydrotreatment.[5] Renewable forms of biodiesel have the same chemical properties as conventional fossil-fuel derived diesel, thus eliminating blend limits (Tuli & Kasture, 2022). Currently, renewable diesel is produced using first- or second-generation feedstocks, but third-generation could also be used.

In 2019, global consumption of biodiesel for trucking was dominated by FAME with 41,500 million liters, compared to HDRD at 5,900 million liters, but global trends suggest

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[4] Transesterification is a chemical reaction that converts triglycerides (fats) contained in oils into a usable biodiesel (Quader & Ahmed, 2017)

[5] Hydrotreatment is the reaction of organic compounds from vegetable oils and other feedstocks in the presence of hydrogen to remove oxygen and other chemicals (Dumbre & Choudhary, 2020)

the latter is growing at a faster rate (International Energy Agency, 2021; Tuli & Kasture, 2022). While traditional biodiesel is currently produced at large-scale and near cost-competitive with fossil fuels, the opportunity to expand usage is constrained by issues such as competition with land for food production and forestry (Subramaniam et al., 2019) Some experts argue that renewable diesel may be a promising alternative as feedstocks include plant and animal waste and algae which reduce food security concerns raised from first-generation biofuels (Rauch et al., 2013). In the agricultural industry 70% of food crops is non-digestible and typically burned, so rather than using edible crops for bioenergy, renewable biodiesel can make use of this agricultural waste (Rauch et al., 2013). Using algae as a biomass feedstock may provide further advantages: it is grown in water thus reducing land-use concerns and has a faster growth rate than other feedstocks (Saha et al., 2019). Second and third generation biofuels may alleviate food security concerns, but both have drawbacks such as their higher costs compared to first-generation biofuels. And, if these biofuels become major players in the make-up of our energy system, it is likely that additional drawbacks will be uncovered.

Possible production methods for second- and third-generation biofuels include the biomass-to-liquid (BTL) via gas-to-liquid (GTL) method and pyrolysis.[6] These production methods are at the pilot project development stage because of high upfront costs that hinder production and inadequate prices on GHG pollution from burning low-cost conventional diesel. Indeed, these methods are often two to six times more expensive than first-generation methods (International Renewable Energy Agency, 2013). As a result biofuels using these processes require climate policies consistent with prevention of major climate change to be competitive with conventional fossil fuel-derived diesel (Clarke et al., 2021).

Trucks that use biodiesel to power their engine include conventional diesel trucks and biodiesel (or flex-fuel) trucks. For this paper, I will exclusively use the term flex-fuel truck to refer to trucks with internal combustion engines, a fuel tank, and specialized parts to allow for the use of conventional biodiesel, a flexible combination of diesel with any

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[6] The BTL via GTL method converts solid biomass into a synthesis gas (carbon monoxide and hydrogen) which can then be converted into liquid via the Fischer-Tropsch process. Pyrolysis is a simpler production method that utilizes catalytic technology to convert solid biomass directly to a liquid fuel.

biodiesel, or renewable diesel. Flex-fuel trucks only cost 10% to 25% more than diesel trucks (den Boer et al., 2013; Fulton & Miller, 2015; Moultak et al., 2017). Unlike hydrogen and electric trucks, flex-fuel truck capital costs are more certain because the parts are near-identical to the parts used in diesel trucks. Finally, flex fuel trucks refuel at the same rate as diesel trucks and have only a slightly smaller range due to the lower fuel content of most biodiesel (Sims et al., 2014). As noted, conventional diesel trucks can also run using biodiesel – with conventional biodiesel blended up to 20%, and renewable diesel up to 100%. For a conventional truck to blend conventional biodiesel (such as FAME) beyond 20%, vehicles need specialized equipment (Alleman et al., 2016).

Biodiesel is already blended with diesel at existing diesel fueling stations, at approximately 3% in Canada (Navius Research, 2021). If FAME remains the dominant biodiesel on the market, blends can be increased to 20% without modification of infrastructure, otherwise storage tanks must be improved to store higher blends of FAME. A modified station is slightly more expensive than current diesel stations, but costs are more certain because the technologies needed are already established. Renewable diesel (e.g., HDRD) can utilize existing diesel infrastructure, so station modifications would be unnecessary if consumption of this biofuel increased.

Chapter 3. Methods

To assess the potential market contributions of zero-emission technologies to a zero-GHG road freight sector, I updated and employed the CIMS model. In this chapter, I provide a general overview of CIMS. Then I describe the updates I made to the model, including disaggregation of road freight, adding zero-emission technologies and their infrastructure, and updating existing road freight technologies. I conclude this chapter with an overview of the scenarios and simulations I developed to assess the likely contribution of zero-emission trucks to a zero-GHG road freight sector.

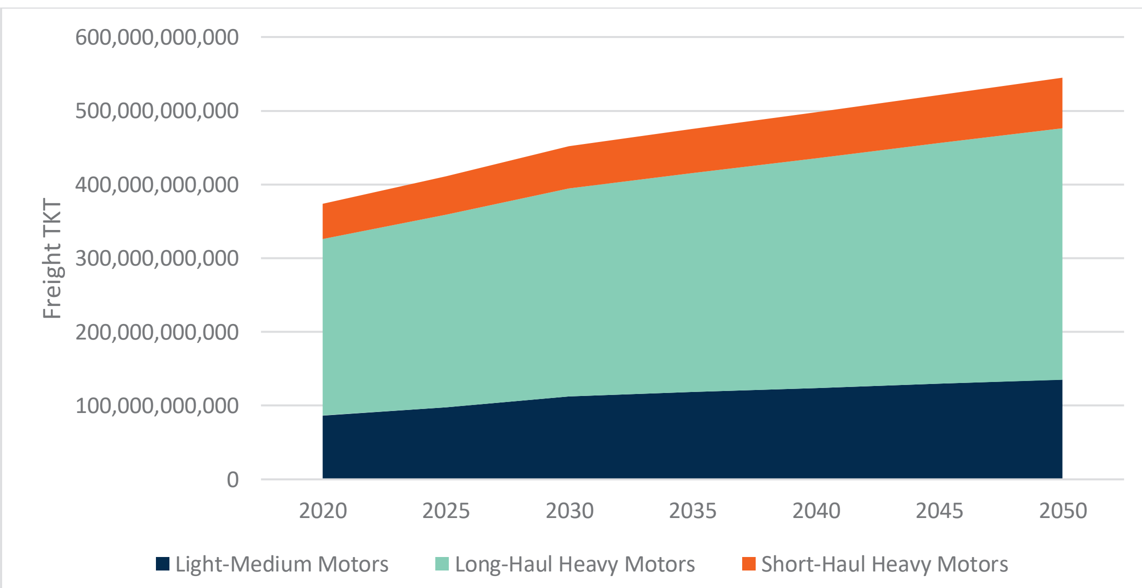
3.1. CIMS Overview:

The Canadian Integrated Modeling System (CIMS) is a hybrid energy-economy model developed at the Energy and Materials Research Group in the School of Resource and Environmental Management at Simon Fraser University. CIMS tracks the evolution of energy-producing and energy-consuming technologies as their stocks change over time due to changes in market conditions (Jaccard, 2009). Market conditions that influence stock include energy costs, stringency of governmental policies, and new technologies entering the market. I chose to use CIMS because it is a technologically explicit model which includes a wide range of technology options, while incorporating behavioral realism. In a technologically explicit model, each technology has its own capital and operating cost and energy use profile. Technologies compete in a model simulation and from this CIMS provides the market share for each truck type. This explicitness is useful when forecasting the technological possibilities that may occur as climate policy is applied to an economic sector (Rhodes et al., 2022). Behaviorally realistic models account for human preferences when making purchasing decisions, such as decisions on which freight truck to purchase. CIMS allowed me to combine the tendency for firms to maximize profits with imperfect decision making due to other preference factors like relative convenience, risk, and service of any technology.

I used a national version of CIMS to assess the Canadian road freight sector. CIMS groups provinces into seven economic regions: British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, and Atlantic. The Atlantic provinces are grouped together due to their smaller energy and emissions profiles compared to other provinces. Within each region, the model includes economic sectors that supply or demand energy. The road freight sector is a demand sector that requires energy inputs, which potentially include diesel, natural gas, hydrogen, electricity, and biodiesel. Fuel costs are entered exogenously or through the endogenous simulation of energy supply. In my version of the CIMS model, energy supply sectors are de-activated so that I could set energy costs exogenously to reflect external conditions such as oil price and bioenergy costs.

In the road freight sector, the demand for freight transport is set exogenously based on a forecast of population and economic growth. That demand is measured in tonne kilometer travelled (TKT). *Figure 1* shows the forecasted demand for road freight to 2050 taken from the annual "Report on Energy Supply and Demand in Canada" produced by Statistics Canada (Statistics Canada, 2021b). CIMS had two road freight modes: Light-Medium Motors and Heavy Motors. I created a third mode by disaggregating Heavy Motors into Long-Haul Heavy Motors and Short-Haul Heavy Motors.

Figure 1: Road Freight Demand Forecast



In each five-year period, trucks at the end of their expected life are assumed to be retired. Next, the model assesses whether the remaining truck stock will meet forecasted demand, and, if not, new trucks will compete to enter the market. This process repeats from 2020 to 2050.

To determine which technologies will capture new market share, CIMS compares life-cycle costs of each technology using the equation below:

Equation 1. CIMS Market Share

$$MS_j = \frac{\left[CC_j * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j + i_j\right]^{-v}}{\sum_{k=1}^{K}\left\{\left[CC_k * \frac{r}{1-(1+r)^{-n_k}} + MC_k + EC_k + i_k\right]^{-v}\right\}}$$

In *Equation 1*, the life-cycle cost of technology (j) is compared to the sum of the life-cycle costs of all competing technologies (k) to determine the market share of technology (j). The life-cycle cost of a technology is influenced by financial costs, including capital (CC), maintenance (MC), and energy (EC), and behavioral parameters. The behavioral parameters are discount rate (r), market heterogeneity (v), and intangible costs (i).

The discount rate captures time preferences of decision-makers who value present returns over future ones. It annualizes the capital cost of a technology to show the present value of equal annual payments over the lifespan of a technology. I used a private discount rate to represent how individual firms (like freight truck operations) make private decisions to maximize their own profits (Environmental Protection Agency, 2010). I set my discount rate to 25% which was empirically estimated from stated and revealed choice research (Horne et al., 2005; Mau et al., 2008). This rate emphasizes short-term costs and benefits over long-term ones which may hinder the adoption of technologies with longer payback periods and fuel saving potential. It reflects the tendency of decision-makers to focus on present costs (truck purchase) over future costs (operating).

The v-parameter represents market heterogeneity. A high value tends toward homogeneity where the technology with the lowest cost will capture most of the market. Low heterogeneity represents a market with an even spread of technologies because market share is influenced by perceived cost, rather than actual cost. In a commercial industry like road freight, a higher v-parameter is used to represent how firms are mostly cost-focused decision makers who want to maximize profits by purchasing the cheapest technologies (DellaVigna, 2009). I have chosen a v-parameter of 15, which is in line with other road freight modeling, which in turn was based on the literature of trucking industry technology acquisition (Hammond et al., 2019; Lepitzki & Axsen, 2018; Vass, 2016).

Intangible costs represent all non-financial costs a consumer or firm faces when purchasing a technology. In road freight these costs include perceived risk of a new technology and range anxiety. In this project, I set the intangible costs to zero for all trucks. Unlike individuals purchasing personal vehicles, truckers must focus on minimizing purchase costs and operating costs if they are to survive in a highly competitive industry (DellaVigna, 2009; Dixon, 1992). I addressed technology-specific uncertainties via my scenario analysis, which I describe in later sections.

In the market share equation, capital costs are not fixed for newer zero-emission technologies. Over time, these costs fall due to innovations and development of new technologies and economies-of-scale as more products are sold. Economies-of-scale and economies-of-learning are endogenous to the model and represented by the declining capital cost function, shown in *Equation 2*.

In *Equation 2*, CC is the capital cost of technology (t). GCC is the capital cost of a technology adjusted for cumulative stock in other countries. $CumulNS_{2020,p}$ is the cumulative new stock of a technology for all years up to and including the year 2020 in each province. NS_{jp} is the new stock of a technology added from 2005 to the previous time period in each province. PR is the progress ratio, which represents the cost decrease in response to a doubling in cumulative production.

Equation 2. Declining Capital Cost

$$CC_t = GCC_t * \left[\left(\sum_{1}^{p} \frac{CumulNS_{2020,\mathrm{p}} + \sum_{j=2005}^{j=t-5} NS_{jp}}{CumulNS_{2020,\mathrm{p}}} \right)^{\log_2(PR)} \right]$$

In CIMS, capital costs also decline exogenously through the exogenous rate of decline (AEEI), as shown in *Equation 3*. The AEEI represents cost declines that happen independent of the model simulation, such as technological learning in other countries.

Equation 3. Exogenous Capital Cost Decline

$$GCC_t = GCC_{t-5} * (1 - AEEI)^5$$

3.2. Model Updates:

3.2.1. Vehicle Modes

Canada's road freight sector is classified generally into light-heavy, medium-heavy, and heavy-heavy duty, but also into sub-classes within these categories as shown by the left column of *Table 1*. For my thesis, I combined light and medium-duty trucks into one mode called Light-Medium Motors. This mode represents lighter, short-haul trucks. Previously in CIMS, heavy-duty vehicles existed under one mode called Heavy Trucks which included short and long-haul types. Research indicates that zero-emission trucks may face different adoption barriers depending on haul type (den Boer et al., 2013; Fulton & Miller, 2015; Moultak et al., 2017). And, previous researchers have cited the lack of haul type as a limitation of their road freight modeling (Hammond et al., 2019; Lajevardi et al., 2019). To represent differences in haul, I split Heavy Trucks into Long-Haul Heavy Motors and Short-Haul Heavy Motors. The technologies in each vehicle mode do not compete as they have different functions. *Table 1* highlights these differences between the Canadian road freight classification system and my representation in CIMS for the purpose of GHG policy modelling and scenario analysis of technology uncertainty.

Table 1. Vehicle Modes in Canada and in CIMS

Vehicle Class	Canada's Heavy Duty Vehicle Mode Designation	CIMS Heavy Duty Vehicle Mode Designation
Class 2b	Light-Heavy Duty Vehicle	Light-Medium Motors
Class 3	Light-Heavy Duty Vehicle	Light-Medium Motors
Class 4	Medium-Heavy Duty Vehicle	Light-Medium Motors
Class 5	Medium-Heavy Duty Vehicle	Light-Medium Motors
Class 6	Medium-Heavy Duty Vehicle	Light-Medium Motors
Class 7	Heavy-Heavy Duty Vehicle	Short-Haul Heavy Motors
Class 8	Heavy-Heavy Duty Vehicle	Long-Haul Heavy Motors

Each truck mode demands a different level of TKT, depending on annual distance travelled and payload capacity. A light-medium motor demands the fewest TKT because these trucks drive the shortest distances and have the lightest payloads. On average, light-medium trucks drive 23,300 km/year, carrying 3.6 tonnes of goods (Natural Resources Canada, 2020; US Department of Energy, 2012). While an individual truck may have low TKTs, 20% of total road-freight TKT is provided by Light-Medium Motors due to their large vehicle stock. In 2019, 93% of the road-freight sector was Light-Medium Motors (Natural Resources Canada, 2020). A long-haul heavy truck provides the most TKTs because they drive an average of 93,000 km per year and carry an average of 17 tonnes of goods (National Research Council, 2010; Natural Resources Canada, 2020). In contrast, short-haul heavy trucks drive an average of 25,000 km per year, carrying approximately 16 tonnes (National Research Council, 2010). In 2019, short and long-haul heavy trucks represented 6.7% of trucks on the road, yet 76% of TKT came from Long-Haul Heavy Motors and 3% from Short-haul Heavy Motors. Short-haul heavy trucks accounts for a small percentage of road-freight TKT in Canada because they have the lowest vehicle stock of all modes. *Table 2* summarizes the key differences that inform TKT between each vehicle mode in CIMS and annual TKT demand.

Table 2. TKT per vehicle and annual TKT Demand for Each Vehicle Mode

CIMS Heavy Duty Vehicle Mode	Average Annual Kilometers Travelled	Average Payload (tonnes)	Average TKT per vehicle per year	Percent of Road-Freight Demand in Canada
Light-Medium Motors	23,319	3.62	83,260	20%
Short-Haul Heavy Motors	24,791	15.88	393,686	3%
Long-Haul Heavy Motors	93,279	17.01	1,586,681	76%

Table 3 summarizes the available technologies used in CIMS and the fuel types used for each truck. Each road freight mode has diesel, electric, plug-in hybrid, hydrogen, flex-fuel, and natural gas drivetrain technologies. For diesel trucks, I included standard engines and two alternative engines with improved efficiency. Each diesel engine has a

maximum blend of 20% biodiesel. In my version of CIMS, conventional biodiesel and renewable diesel are combined into one fuel called Biodiesel. As a result, I could not allow for a higher blend of biodiesel in internal combustion engines as the fuel supplied may have been conventional biodiesel that is limited by the blend limit. In Light-Medium Motors, I included a hybrid vehicle that operates using diesel but has higher efficiency due to the assistance from its battery. I did not include a hybrid truck in short or long-haul trucks because hybrid has not been pursued as an option in these modes (Stinson, 2021). Long-Haul Heavy Motors have an additional electric drivetrain option: catenary trucks. I did not include catenary for light-medium or short-haul heavy motors because catenary trucks have their best prospects for long-distance, highway driving likely on freight corridors.

Table 3: Available Vehicle Technologies and Fuel Type(s) used by mode

Drivetrain Technology	**Fueling Options**	
	Light/Medium Truck	*Heavy Truck (Long & Short-Haul)*
Diesel	Diesel or Biodiesel Blend (up to 20%)	Diesel or Biodiesel Blend (up to 20%)
Diesel Medium Efficiency	Diesel or Biodiesel Blend (up to 20%)	Diesel or Biodiesel Blend (up to 20%)
Diesel High Efficiency	Diesel or Biodiesel Blend (up to 20%)	Diesel or Biodiesel Blend (up to 20%)
Hybrid	Diesel or Biodiesel Blend (up to 20%)	
Natural Gas	Natural Gas only	Natural Gas only
Hydrogen Fuel Cell	Hydrogen Only	Hydrogen Only
Battery Electric	Electricity Only	Electricity Only
Plug-in Hybrid	Electricity or Diesel or Biodiesel Blend (up to 20%)	Electricity or Diesel or Biodiesel Blend (up to 20%)
Flex Fuel	Diesel or Biodiesel Blend (up to 100%)	Diesel or Biodiesel Blend (up to 100%)
Catenary*		Electricity Only

* There are no catenary trucks in the short-haul heavy mode

I set Light-Medium Motors and Short-Haul Heavy Motors to retire after 16 years of operation. Long-haul trucks break down faster and need to be replaced sooner because of the extra distance and weight they carry. Therefore, I set Long-Haul Heavy Motors to retire after 12 years. Long-haul trucks typically drive on highways at consistent speeds, whereas short-haul and light-medium vehicles operate in urban centers, experiencing long idling times and stop-start driving due to congestion and traffic lights. These differences influence the efficiency of heavy-duty vehicles. Fuel efficiency is the measure of the amount of energy used per TKT. *Table 4* indicates the efficiency I set for each vehicle, based on data found in literature. For short-haul heavy-duty motors, I decreased the efficiency for internal combustion engines by 30% to account for city driving. Hydrogen and electric drivetrains have better efficiency than internal combustion engines and I kept efficiency for hydrogen and electric trucks consistent for long and short-haul motors because these trucks are not commercially used, so fuel efficiency in different driving conditions is still uncertain.

Table 4. Vehicle Fuel Efficiency in Each Mode

Drivetrain Technology	Fuel Efficiency (MJ/TKT)			Source
	Light/Medium Truck	Short-Haul Truck	Long-Haul Truck	
Diesel	1.5	1.196	0.92	(den Boer et al., 2013; Moultak et al., 2017)
Diesel Medium Efficiency	1.35	1.079	0.83	(U.S. Energy Information Administration, 2016)
Diesel High Efficiency	1.22	0.962	0.74	(U.S. Energy Information Administration, 2016)
Hybrid	1.08			(U.S. Energy Information Administration, 2016)
Natural Gas	1.6	1.248	0.96	(den Boer et al., 2013; Moultak et al., 2017)
Hydrogen Fuel Cell	1.05	0.6	0.6	(den Boer et al., 2013; Moultak et al., 2017)
Battery Electric	0.8	0.55	0.55	(den Boer et al., 2013; Moultak et al., 2017)
Plug-in Hybrid	1.25	0.44	0.624	(den Boer et al., 2013; Moultak et al., 2017)
Flex Fuel	1.58	1.235	0.95	(den Boer et al., 2013; Moultak et al., 2017)
Catenary Truck			0.55	(den Boer et al., 2013; Moultak et al., 2017)

3.2.2. Infrastructure

I added infrastructure technologies to CIMS for each zero-emission vehicle to understand how refueling / recharging infrastructure costs may influence adoption of zero-emission trucks. In CIMS, each vehicle demands infrastructure that delivers energy at the same rate the vehicle consumes energy. For example, each electric charging station can provide up to 1,767 GJ of electricity to electric trucks in the road freight sector each year. An electric truck will require gigajoules of infrastructure at the same rate at which it deplete its electricity reserve. So, an electric truck with a fuel efficiency of 0.8 MJ per TKT will demand 0.8 MJ per TKT of infrastructure. Battery electric and plug-in hybrid trucks require electric depot and on-road charging stations (Johnson et al., 2020). Depot chargers have a lower power level, while on-road chargers require a higher power level for rapid charging.

Catenary trucks require on-road catenary wire infrastructure (Park & Jeong, 2017). Experts at the Oak Ridge National Laboratory predict that on-road charging could exist on 8% of roads, while remaining cost-effective (O. Omer, personal communication, November 3, 2021). I assume major freight corridors, such as the 380 km route between Edmonton and Calgary, could install catenary wires. Catenary wire costs were based on a catenary road similar in length to the Albertan freight corridor in each province.

Hydrogen trucks will likely require low and high capacity hydrogen refueling stations (Melaina et al., 2012). I included both types of stations because experts expect that infrastructure roll-out will begin with low-capacity stations. As demand for hydrogen increases, larger stations with higher storage capacities will be installed. For this reason, low-capacity stations became available in 2020, while high-capacity stations were delayed until 2025.

For flex-fuel trucks, the model determines the mix of fuel each truck will receive. A flex-fuel truck can receive four different mixes: pure diesel, B05 (5% biodiesel), B20 (20% biodiesel) or B100 (pure biodiesel). The mix is determined through the market share equation and thus depends on relative life-cycle costs. Flex-fuel trucks using pure diesel, B05, or B20 can refuel at existing diesel stations. If it is economical to use B100, new infrastructure is required since B100 may contain conventional biodiesel that requires specialized equipment. *Table 5* summarizes the key technological parameters I used for zero-emission truck infrastructure.

Table 5: Parameterization of Infrastructure for Zero-Emission Vehicles

Station Type	Fuel Provided	Fuel Output (GJ/year)	Capital Cost	Source	Annual Operating Cost	Source
Depot Charger	Electricity	1767	$76,000	(Hall & Lutsey, 2019; Johnson et al., 2020)	$458.41	(den Boer et al., 2013; Johnson et al., 2020)
Rapid Charger	Electricity	8204	$310,000	(Hall & Lutsey, 2019; Johnson et al., 2020)	$9,509.00	(den Boer et al., 2013; Johnson et al., 2020)
Catenary Wires	Electricity	1,241,975	$1,365,470,000	(den Boer et al., 2013; Moultak et al., 2017)	$281.751	(den Boer et al., 2013; Moultak et al., 2017)
Low-Capacity Station	Hydrogen	20,146	$639,992	(International Energy Agency, 2019b)	$48,365	(Weinert et al., 2007)
High-Capacity Station	Hydrogen	53,016	$2,179,309	(International Energy Agency, 2019b)	$67,711.00	(Weinert et al., 2007)
Biodiesel Refueling Station	Biodiesel	48,354	$63,058	(National Renewable Energy Laboratory, 2008)	$458.41	(National Renewable Energy Laboratory, 2008)

3.3. Scenario Overview:

Global greenhouse gas mitigation efforts will influence the makeup of Canada's road freight sector, but to what extent is uncertain. To capture the uncertainty in mitigation effort at the global level, I created two scenarios. Global Action is when most of the key countries are rapidly reducing GHG emissions. Global Inaction is a continuation of a slow global effort, meaning that Canada is acting alongside only a few leading countries, with little influence on oil markets and even technology evolution. Thus, these scenarios differ in two ways with respect to the focus of my study: the global price of oil and the pace of technological change for low-emission technologies.

3.3.1. Global Oil Market:

The level of global climate action influences the price of oil and associated refined petroleum products. In a Global Action scenario, a switch to zero-emission energy sources would decrease the demand for oil, leading to aggressive competition that eliminates high-cost producers as the oil price falls over the years and decades. In a Global Inaction scenario, the current oil-dominated energy system would face less competitive pressure as demand remains at current levels. Currently, the price of oil directly affects the road freight sector because most trucks run on diesel.

I obtained two global oil price forecasts from the 2018 report from the Canadian Energy Regulator (CER) titled "Canada's Energy Future 2018". The global oil price trajectory and the resulting impacts on diesel fuel prices in 2050 are reflected in *Table 6*.

Table 6: Oil and Diesel Price in 2050

Scenarios	Oil Price Trajectory (Western Texas Intermediate: ($/bbl), 2019 USD)	Oil Price Trajectory (Western Texas Intermediate: ($/bbl), 2019 CAD)	Diesel Price ($/L, before carbon price, 2019 CAD)
Global Action	$40	$53	$1.04
Global Inaction	$70	$93	$1.36

Under Global Inaction, the global oil price rises to $70 USD per barrel by 2050 due to continued demand for fossil fuels, which is equivalent to $93 CAD per barrel. Because the price of oil remains high, diesel prices in 2050 are $1.36 per liter. In the Global Action scenario, the oil price sits at $40 USD ($53 CAD) per barrel in 2050 due to lower demand, thus, lowering the cost of diesel. The price of oil is volatile, so these oil prices represent only two potential averages to assess how uncertainty in oil prices influences the market share of zero-emission technologies in the road freight sector.

3.3.2. Pace of Technological Change:

Global GHG mitigation efforts will influence the pace of technological change. Under my Global Action scenario, strong global climate policies cause greater adoption of zero-emission technologies which will reduce capital costs due to economies-of-scale and economies-of learning. Under Global Inaction, the continued dominance of fossil-fuel based technologies would slow innovation and adoption, and thus cost decline, of zero-emission technologies.

I simulate the pace of technological change by adjusting the autonomous energy efficiency index (AEEI) for zero-emission trucks. The AEEI represents the rate capital costs decline due to forces external to the model, such as production, economies-of-scale, and economies-of-learning in other parts of the world. Thus, I set the AEEI lower to represent a slower pace of change in Global Inaction and higher to represent a faster pace of change in Global Action.

Table 7 shows the capital cost evolution of batteries and fuel cells from 2020 to 2050. I used these cost evolutions to inform the AEEI of hydrogen and electric trucks. Changes in capital costs for batteries were taken from the Canada Energy Regulator's Energy Future 2020 report. Changes in costs for fuel cells were derived from the International Energy Agency's Future of Hydrogen (2019) report. Flex-fuel trucks are cost-competitive to diesel trucks, so stronger global climate policy would not result in large cost declines. Therefore, I held the AEEI for flex-fuel trucks constant in both scenarios.

Table 7: Evolution of the capital costs of key technologies under two scenarios

Scenario	% Change in Capital Costs 2020-2050	
	EV Batteries	*Hydrogen Fuel Cell*
Global Action	-60%	-60%
Global Inaction	-35%	-40%

3.4. Simulations:

In this section, I describe the simulations I ran under Global Action and Global Inaction. These include simulations that alter the level of domestic action in Canada, as well as simulations to alter technological parameters like fuel, infrastructure, and vehicle costs. Each simulation is designed to assess how uncertain technological parameters may influence the market share of zero-emission trucks. I developed 15 simulations which were each run under Global Action and Global Inaction. I excluded two simulations from my results which will be explained in Chapter 4. *Table 8* is a summary of every simulation I ran and under which scenario.

Table 8: Summary of Model Simulations

Simulations		Global Inaction Scenario	Global Action Scenario
Level of Domestic Action	BAU	X	X
	Net-Zero	X	X
Energy Cost	Expensive Hydrogen	excluded	excluded
	Cheap Hydrogen	X	X
	Expensive Biodiesel	X	X
	Cheap Biodiesel	X	X
	Expensive Electricity	X	X
	Cheap Electricity	X	X
Vehicle Cost	Expensive Hydrogen Trucks	excluded	excluded
	Cheap Hydrogen Trucks	X	X
	Expensive Electric Trucks	X	X
	Cheap Electric Trucks	X	X
Infrastructure Cost	Cheap Charging Stations	X	X
	Cheap Catenary Wires	X	X
	Cheap Hydrogen Stations	X	X

3.4.1. Domestic Action Simulations

I developed two simulations to alter the level of domestic action in Canada: BAU and Net-Zero. In domestic action simulations, all technological parameters are set to their baseline estimate. First, I ran a Business-as-Usual (BAU) simulation under each scenario. In BAU, I assume that climate policy stringency will not increase, and Canada will fail to meet climate commitments. The BAU simulation has a carbon price starting at $10 in 2020, rising to $50 by 2022, and remaining at $50 to 2050. The carbon price is currently at $50, and I assume it will remain there.[7]

Next, I ran a Net-Zero simulation to represent 70% emission reduction in road freight in Canada. In Net-Zero, the carbon price rises to $170 by 2030 to match the carbon price schedule set by the federal government. From 2030 to 2050, the carbon price increases to achieve 70% emission reduction in the road freight sector. I have chosen to reduce emissions 70% for two reasons. First, many experts expect that, even with aggressive climate policies, emission reductions in road freight will not reach 100% by 2050 (IPCC, 2022). Second, my simulations suggest that the carbon price must rise to levels far higher than the already extremely high prices needed for me to achieve more than a 70% emissions reduction by 2050.

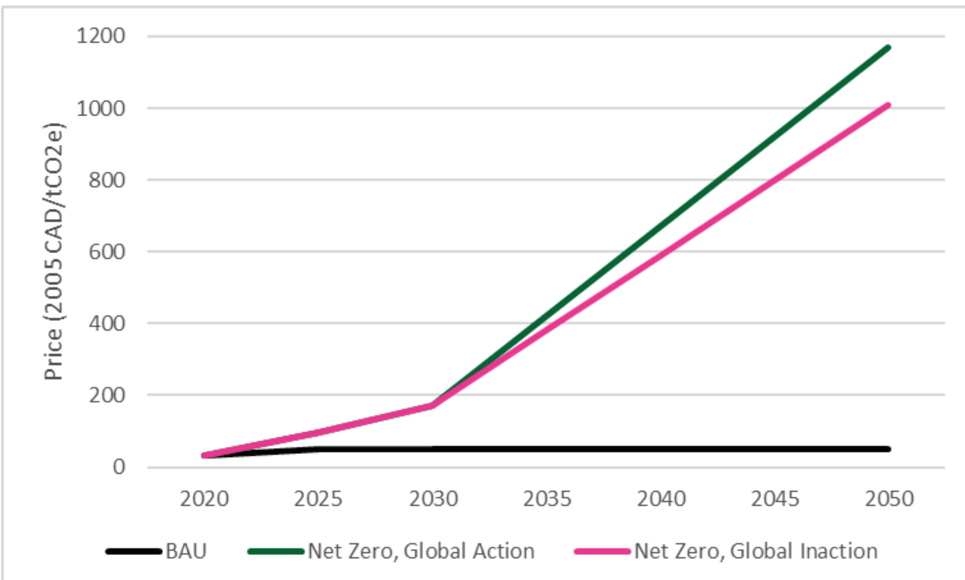
Thus, in my Global Action, the carbon price rises to $1,170 per tonne CO_2 in 2050 to achieve 70% reduction and in Global Inaction it rises to $1,010. Note that to achieve the same 70% reduction in both scenarios, the carbon price must actually rise higher in the Global Action scenario because the price of oil falls to low levels in this scenario, which in turn disadvantages zero-emission technologies. The carbon price must quickly increase to ensure that zero-emission trucks dominate the new truck market long before 2050 (given the long time required to turn over the entire truck fleet). *Figure 2* shows the carbon price schedules in BAU and Net-Zero for each scenario. The BAU scenario uses the same carbon price schedule in Global Action and Global Inaction.

An important point in interpreting *Figure 2* is to remember that CIMS is a partial equilibrium model. If I had used a general equilibrium model, these rapidly rising carbon prices would rapidly increase freight transport costs, which in turn would reduce the

[7] Since conducting this research, the federal proposal to increase the carbon price to $170/tonne CO_2 has been enacted which was not reflected in the BAU simulation I modeled.

demand for freight and lower emissions. Thus, emissions from this sector would fall because of both technological change and the declining demand for freight transport. It would also cause some mode shifting from road freight to train freight, whose cost per tonne kilometer transported is less affected by the rising carbon price. The net effect of these responses is that a 70% reduction target would be achieved at a much lower carbon price. Overall, when interpreting my results, it is important to recognize that a partial equilibrium model gives an inflated estimate of how high the carbon price would have to rise to achieve by 2050 a 70% emission reduction target in the road trucking sector.

Figure 2: Carbon Price Schedule for the Business-as-Usual Simulation and Net-Zero Simulation for Global Action and Inaction



3.4.2. Vehicle Cost Simulations

In the vehicle cost simulations, I altered the capital costs of trucks to assess how this uncertain variable may influence the likely contribution of zero-emission trucks. The cost of most zero-emission heavy-duty trucks is highly uncertain because few trucks are available on the market today. Each simulation was run under Global Action and Inaction and the carbon price increases to achieve 70% emission reduction, derived from the Net-Zero simulation.

The research literature reveals a wide diversity of cost estimates for hydrogen trucks, so I compared baseline values with the cheapest and most expensive estimates. In the Cheap Hydrogen Truck simulation, light-medium trucks are 39% cheaper than baseline at $183,000. Short- and long-haul heavy trucks are 33% cheaper at $350,000. In Expensive Hydrogen Trucks, light-medium trucks are 13% higher than baseline at $340,000. Short- and long-haul heavy trucks are 16% more expensive at $608,000.

In the Cheap Electric Trucks simulation, electric truck (BEV) costs for light and medium motors declined 28% from baseline to $195,000 while plug-in hybrid (PHEV) costs declined 15% to $155,000. For short and long-haul, BEV costs fall 27% from baseline to $344,000 and PHEV fall 10% to $247,000. PHEV costs fall less significantly because they have smaller batteries than BEVs. In long-haul, catenary truck costs declined by 6% to $290,000. Catenary trucks do not see costs fall significantly because they have the smallest battery. In Expensive Electric Trucks, light-medium trucks costs increased 12% for BEV to $300,000 and 5% for PHEV to $190,000. For short and long-haul trucks, costs increased 27% for BEV to $592,000 and 2% for PHEV to $280,000. Long-haul catenary trucks see an increase of 6% in costs to $327,000 from baseline.

I did not include a vehicle cost simulation for flex-fuel trucks that operate like diesel trucks because their costs are not likely to vary far from current cost estimates. *Table 9* shows the range of capital costs for Light-Medium Motors and *Table 10* shows the range of costs for Short-Haul Heavy Motors and Long-Haul Heavy Motors.

Table 9. Baseline, Cheap, and Expensive Capital Costs of Light-Medium Motors

Drivetrain Technology	Base Line Capital Costs	Cheap Capital Cost	Expensive Capital Cost	Source
Diesel	$86,358.39			Moultak et al., (2017); Navius Research, (2020)
Diesel Medium Efficiency	$94,230.97			(Meszler et al., 2015; Moultak et al., 2017; Navius Research, 2020)
Diesel High Efficiency	$105,882.95			Meszler et al., (2015); Moultak et al., (2017); Navius Research, (2020)
Hybrid	$147,529.64			Meszler et al., (2015); Moultak et al., (2017); Navius Research, (2020)
Natural Gas	$126,603.00			Fulton & Miller, (2015); Moultak et al., (2017)
Hydrogen Fuel Cell	$300,233	$183,207.29	$338,693.56	den Boer et al., (2013); Moultak et al., (2017); Navius Research, (2020)
Battery Electric	$268,480.89	$193,566.49	$301,653.53	den Boer et al., (2013); Moultak et al., (2017); Navius Research, (2020)
Plug-in Hybrid	$182,445.24	$154,928.64	$191,053.53	den Boer et al., (2013); Moultak et al., (2017); Navius Research, (2020)
Flex Fuel	$115,882.95			Meszler et al., (2015); Moultak et al., (2017); Navius Research, (2020)

Table 10. Baseline, Cheap, and Expensive Capital Costs of Short-Haul Heavy Motors and Long-Haul Heavy Motors

Drivetrain Technology	Base Line Capital Costs	Cheap Capital Cost	Expensive Capital Cost	Source
Diesel	$169,999.66			den Boer et al., (2013); Fulton & Miller, (2015); Moultak et al., (2017); Navius Research, (2020)
Diesel Medium Efficiency	$183,902.33			(den Boer et al., 2013; Fulton & Miller, 2015; Meszler et al., 2015; Moultak et al., 2017; Navius Research, 2020)
Diesel High Efficiency	$201,902.33			(den Boer et al., 2013; Fulton & Miller, 2015; Meszler et al., 2015; Moultak et al., 2017; Navius Research, 2020)
Natural Gas	$262,042.00			(Fulton & Miller, 2015; Moultak et al., 2017)
Hydrogen Fuel Cell	$427,790.86	$351,316.61	$608,314.61	(den Boer et al., 2013; Fulton & Miller, 2015; Moultak et al., 2017; Navius Research, 2020)
Battery Electric	$468,398.67	$344,000.000	$592.296.01	(den Boer et al., 2013; Moultak et al., 2017; Navius Research, 2020)
Plug-in Hybrid	$275,857.52	$247,407.52	$281,307.52	(den Boer et al., 2013; Moultak et al., 2017)
Flex Fuel	$201,921.59			(den Boer et al., 2013; Fulton & Miller, 2015; Meszler et al., 2015; Moultak et al., 2017; Navius Research, 2020)
Catenary	$308,165.00	$289,106.51	$327,106.51	(den Boer et al., 2013; Moultak et al., 2017)

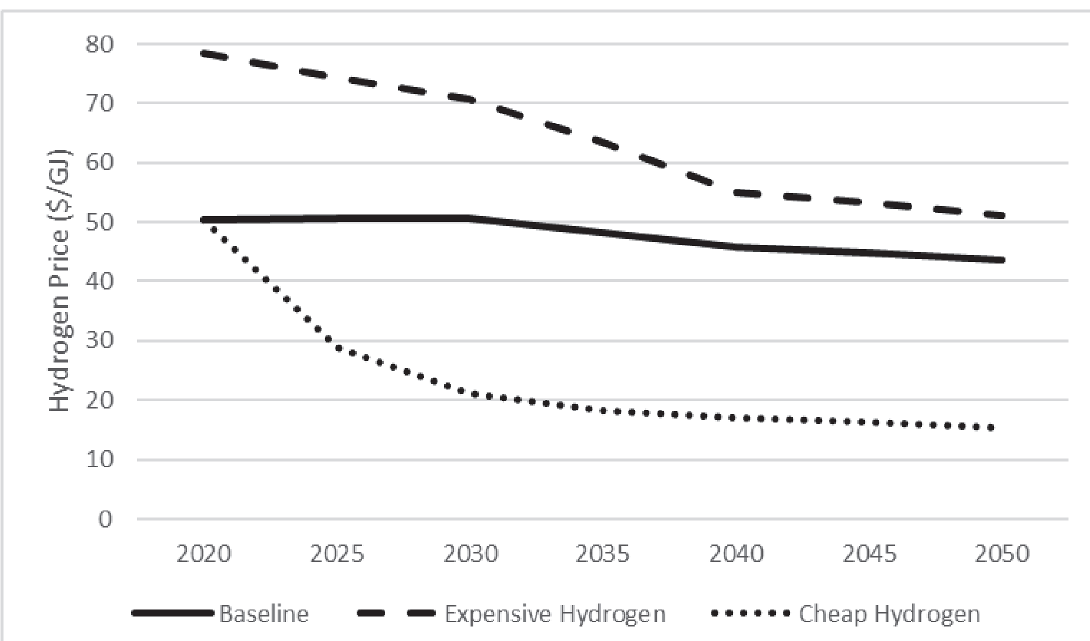
*Catenary costs only applied in Long-Haul Heavy Motors

3.4.3. Energy Cost Simulations

The evolving prices of zero-emission forms of energy, including hydrogen, electricity, and biodiesel, will influence zero-emission truck choices. I ran costs under baseline, cheap, and expensive energy cost estimates. Each simulation was run under Global Action and Global Inaction with a rising carbon price to achieve 70% emission reduction, derived from the Net-Zero simulation.

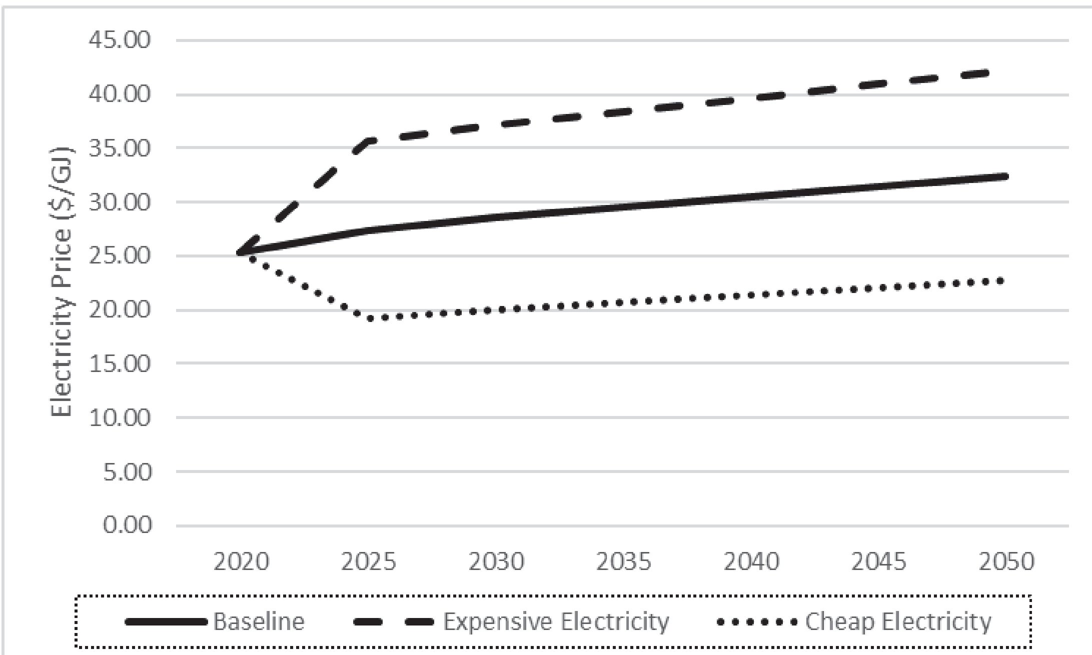
I ran Cheap Hydrogen to represent the lowest hydrogen cost estimate found in literature and Expensive Hydrogen to represent the highest cost. *Figure 3* shows how hydrogen cost evolves over time in each simulation. The baseline value come from the Argonne National Laboratory and includes hydrogen produced through steam methane reforming with CCS and through electrolysis. Cheap Hydrogen values were drawn from two reports that estimate a lower cost evolution for low-carbon hydrogen (Brändle et al., 2021; Kannah et al., 2021). Expensive Hydrogen only includes the cost of electrolysis which is currently significantly higher than methods that rely on fossil fuel feedstocks with CCS, thus the higher cost in 2020 (Ajanovic & Haas, 2018). Expensive Hydrogen represents the unlikely, but possible future where fossil fuel production, regardless of CCS, is completely banned.

Figure 3: Hydrogen Cost Evolution from 2020 to 2050 in Three Simulations



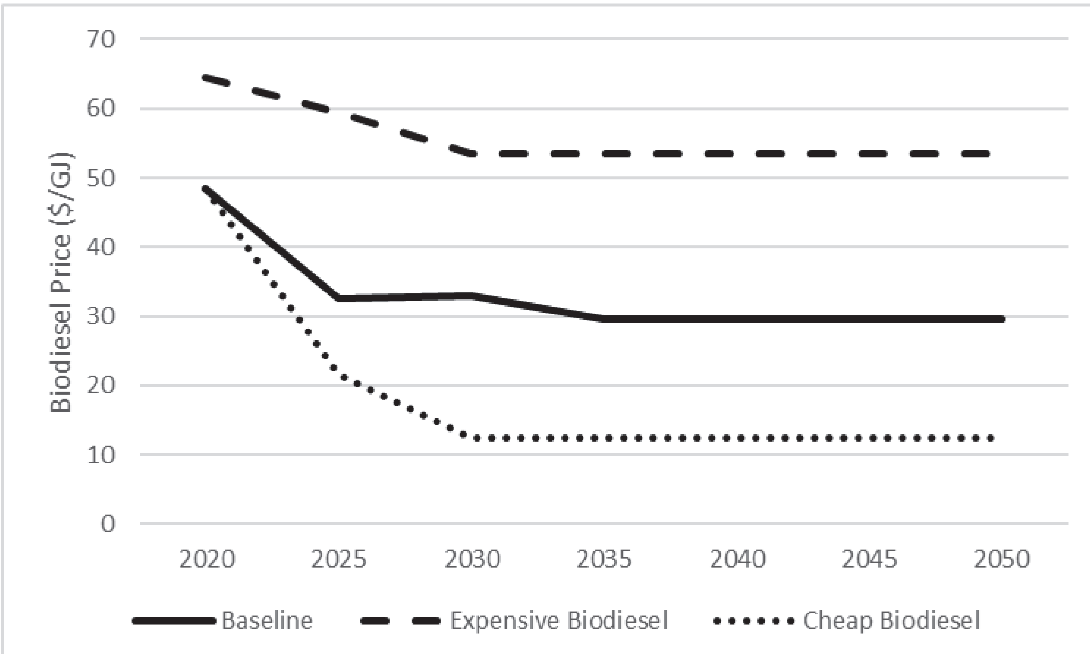
Electricity costs are the most certain of the energies I examined because zero-emission generation is already commercially used at large-scale. I ran three simulations for the cost of electricity. The estimates for the baseline values were obtained from the Canadian Energy Regulator's Energy Futures 2020 Report. In Cheap Electricity, I reduced electricity costs 30% relative to baseline in 2050. In Expensive Electricity, I increased costs by 30%. I used this range of uncertainty to reflect the range used in similar studies examining how uncertainties in energy cost influence the likely contribution of zero-emission vehicles (Hammond et al., 2019; Muncaster, 2008). *Figure 4* shows the cost evolution of electricity in Canada from 2020 to 2050.

Figure 4: Electricity Cost Evolution from 2020 to 2050 in Three Simulations



I combined the costs for conventional biodiesel and renewable diesel into one fuel in CIMS called Biodiesel. I used a report from a Danish consulting company to determine my baseline costs. The Danes are moving faster with biofuel use, so their cost estimates are based on large-scale commercialized production costs (Ea Energy Analyses, 2015). Cheap Biodiesel and Expensive Biodiesel were informed by a 2020 report comparing biodiesel costs (Witcover & Williams, 2020). The Cheap Biodiesel simulation may represent a future where first-generation biodiesels remain the dominant fuel type, allowing for cheaper biodiesel. The Expensive Biodiesel simulation represents a simulation where, for example, first-generation feedstocks are banned due to food security concerns, so second and third generation biodiesel must be utilized starting in 2020, thus capital costs in the expensive simulation are higher in 2020. Estimates from Witcover and Williams (2020) only considered costs to 2030. I assumed that costs would remain stable in real terms from 2030 to 2050. *Figure 5* shows the three cost evolutions for biodiesel in each simulation.

Figure 5: Biodiesel Cost Evolution from 2020 to 2050 in Three Simulations



As I noted earlier, my version of CIMS does not represent global energy markets and for this reason I presented two contrasting scenarios of global oil (and therefore diesel) prices, associated with Global Action and Global Inaction. One could argue that I should have similarly treated biomass (and therefore biodiesel) prices. A greater global effort to reduce GHG emissions is likely to put more pressure on land to produce zero-emission energy substitutes to burning fossil fuels. In this case, though, greater global action would lead to higher biodiesel production costs rather than the lower production costs of oil and oil products as fierce price competition eliminates the highest cost producers.

To keep this study from getting too complicated, I have elected instead to treat biodiesel as I treat electricity and hydrogen, both produced in zero-emission processes. Namely, I make estimates of high and low prices and simulate these conditions. But in each simulation, increases or decreases in demand during the simulation do not cause price changes. In effect, once a price is set exogenously, it is fixed for that particular simulation, implying a flat supply curve and no global market dynamics. A more detailed study might reconsider this simplified approach.

3.4.4. Infrastructure Cost Simulations

I ran simulations for three types of infrastructure: electric charging stations, hydrogen refueling stations, and catenary wires. I did not run expensive cost simulations under Global Action or Global Inaction because after running the Net-Zero simulation I discovered that infrastructure is a very small percent of life-cycle cost on a per TKT basis, so it is unlikely to alter New Market Share significantly. I discuss this further in Chapter 4. Each remaining simulation was run under Global Action and Global Inaction with the carbon price set by the Net-Zero simulation to achieve 70% emission reduction from 2000 levels.

Electric vehicles require electric charging stations to operate. Baseline costs for depot chargers are $76,000 and rapid chargers are $310,000. In Cheap Charging Stations, depot station costs fall 20% to $60,000 and rapid charger costs fall 60% to $128,000 (Bansal, 2015). Depot charger costs are more certain because these operate similarly to personal vehicle charging stations, while rapid chargers are still in early stages of development. Electric charging stations may have an advantage over hydrogen and catenary infrastructure because electric stations can utilize the already existing electricity distribution network.

Hydrogen refueling stations differ in capacity level and where their hydrogen is produced. For my hydrogen refueling station simulation, I incorporated two refueling stations: high and low-capacity stations. In the baseline, the cost for a low-capacity station is $640,000 to install, while the high-capacity station is $2,180,000. In baseline, I assume refueling stations are an even mix of on-site production and delivered hydrogen via truck or pipeline. In Cheap Hydrogen Refueling Stations most stations receive hydrogen from truck or pipeline and low capacity station costs fall 75% to $160,000 while high capacity station costs fall 40% to $1,300,000 (International Energy Agency, 2019b). Hydrogen stations that rely on onsite production have a higher upfront cost because onsite production requires a reformer or electrolyzer coupled with a storage tank and fuel pump, while delivered hydrogen stations only need the tank and pump. Although, delivered hydrogen stations would need an adequate hydrogen distribution network to consistently provide hydrogen to customers and this network does not yet exist. Delivered hydrogen refueling stations for freight trucks would unlikely bear the entire cost of this distribution network as other economic sectors may also rely on the hydrogen network in the future.

Catenary wire infrastructure is expensive as it requires retrofitting entire highways to allow for charging of catenary trucks. The estimated baseline cost of a catenary wire is $1,400,000,000 to install (den Boer et al., 2013) on a 380 km highway. This cost includes capital and installation costs. In Cheap Catenary Wires, costs fall 40% to $820,000,000 (Park & Jeong, 2017).

Chapter 4. Results & Discussion

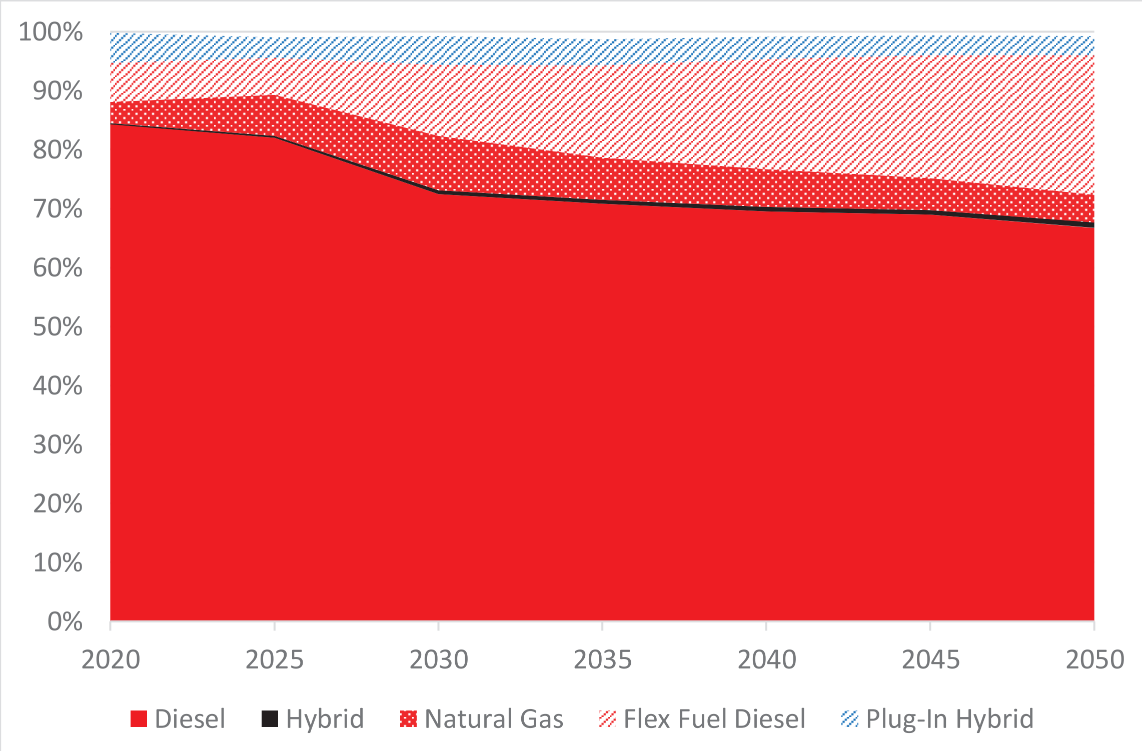
This chapter presents the results of the simulations I described in the previous chapter. I first compare Business-as-Usual results with a US Energy Information Administration market forecast. Next, I review, the Net-Zero policy simulation, including the evolution of New Market Share and vehicle life-cycle cost for each mode. Then, I present the forecasts gathered under each technological simulation to understand New Market Share sensitivity to uncertain vehicle, energy, and infrastructure costs. In each section, I discuss which truck “wins” the market, which I define as capturing 50% or more of New Market Share in 2050.

4.1. Business-as-Usual Forecast

A Business-as-Usual (BAU) simulation is one where there are no additional domestic policies to reduce carbon emissions and technological parameters are set to their baseline values. I ran the Business-As-Usual simulation under both scenarios. *Figure 6* shows New Market Share of truck technologies in BAU with Global Action. Given the assumptions I made, diesel trucks capture most of the market, with new sales of natural gas, flex-fuel using conventional diesel, and plug-in hybrid trucks increasing over time. In this scenario, there are almost no zero-emission trucks adopted. In this scenario, 99% of the fuel used by diesel and flex-fuel trucks is diesel, suggesting that blend limits will not be reached.

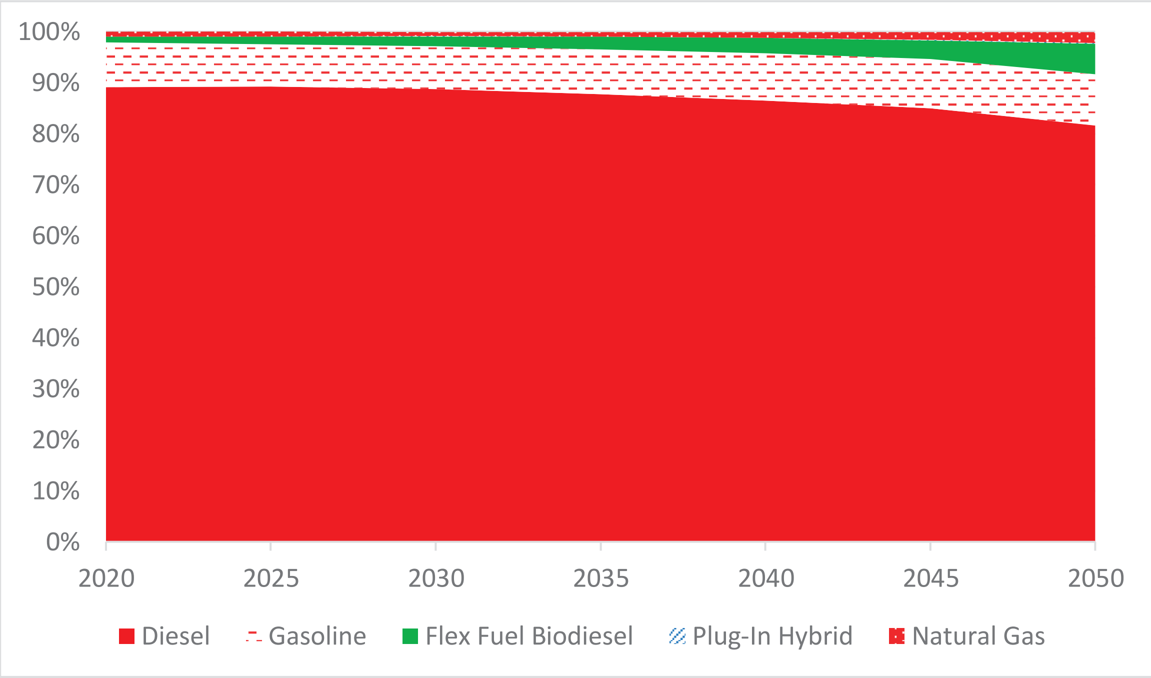
The New Market Share of trucks in BAU, Global Inaction can be found in Appendix A. I have chosen to include the Global Inaction results for all simulations in the Appendix because, for the most part, the level of global mitigation effort did not tip the market in favor on one truck type over another. For example, if flex-fuel trucks won in a Global Action simulation, they also won in the corresponding Global Inaction simulation, to differing extents. Therefore, for simplification, the results from both scenarios will be discussed, while only displaying the results for Global Action. In Global Inaction, diesel trucks win New Market Share as well, but 16% of fuel used in diesel and flex-fuel trucks is biodiesel. Additionally, by 2050, 4% of flex-fuel trucks are running solely on B100. This modest adoption of biodiesel is a result of the high price of oil under Global Inaction, which increases diesel costs, allowing biodiesel to make modest inroads.

Figure 6: BAU, Global Action Scenario Forecast for New Market Share from 2020 to 2050



My results are similar to the US Energy Information Administration's (EIA) baseline forecast of vehicle technologies from 2020 to 2050, shown in *Figure 7* (US Energy Information Adminstration, 2021). In both forecasts, electric and hydrogen trucks do not penetrate the market. The EIA forecast finds that approximately 6% of trucks will use flex-fuel, which is near the range I forecasted for Global Action and Inaction. The EIA modeled gasoline trucks which I chose to incorporate into diesel trucks in my analysis.

Figure 7: **US EIA Forecast of Market Share to 2050**

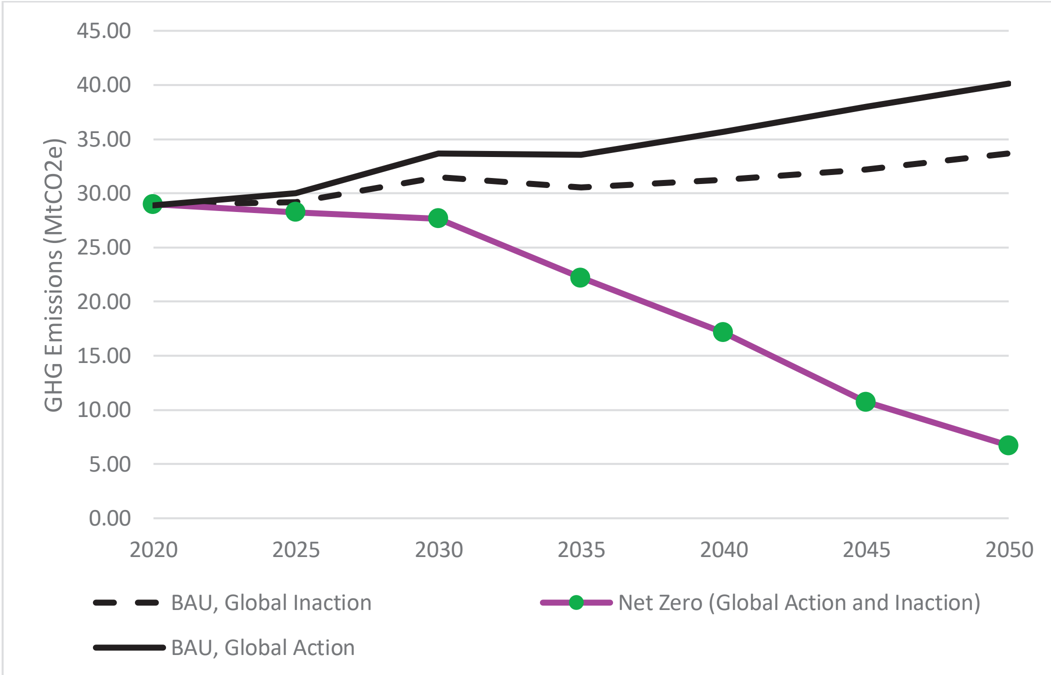


4.2. Net-Zero Forecast

In my domestic Net-Zero simulation, the carbon price achieves 70% emission reduction in on-road freight by 2050 and all technological variables are set to their baseline value. Domestic Net-Zero was run under Global Action and Global Inaction variants.

In *Figure 8*, I show GHG emissions from BAU compared to Net-zero. Net-zero emissions are as expected – they begin falling in 2030 as the carbon price increases and fall to 70% emission reduction in 2050 from 2000 levels. In both BAU simulations, GHG emissions increase from 2025 onwards without a rising carbon price. Emissions are highest in BAU, Global Action because domestic inaction coupled with a low oil price allows for the use of low-cost diesel trucks more so than in Global Inaction.

Figure 8: **GHG Emissions from On-Road Freight in BAU and Net-Zero Simulations**



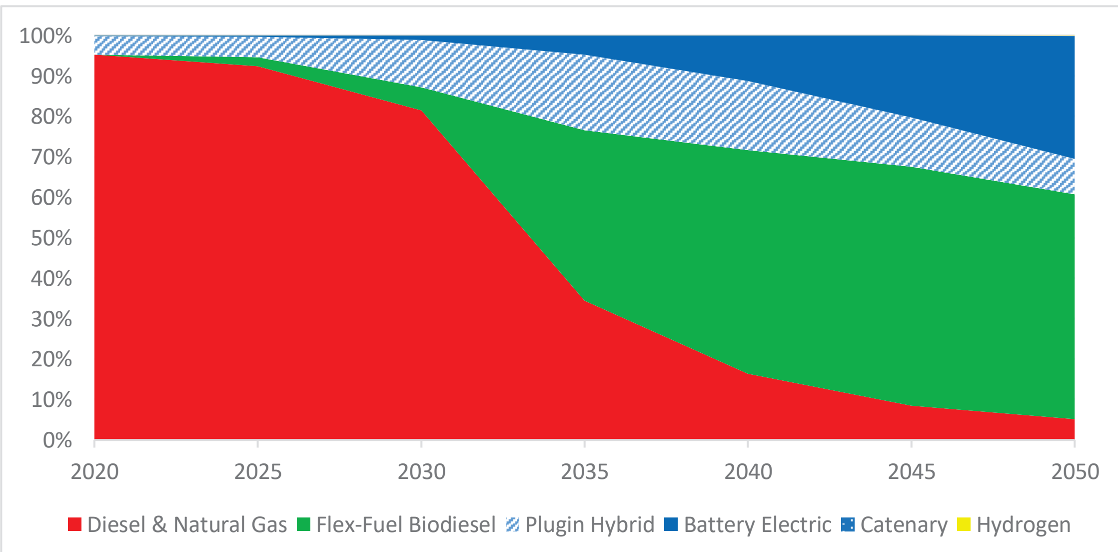
Next, *Figure 9* shows combined New Market Share for light-medium, long-haul heavy, and short-haul heavy trucks in Net-Zero, Global Action. In Global Action when using the baseline parameters, flex-fuel trucks win the market with 56% of truck sales in 2050, battery-electric earn 30%, while no hydrogen trucks are sold. Flex-fuel trucks run solely on B100 by 2050. Diesel trucks capture only a small part of New Market Share with 5% of sales, but by 2050, 20% of the fuel used in diesel trucks is biodiesel, thus reaching the blend limit. Diesel trucks sales begin to fall dramatically only once the carbon price has more than doubled from \$170/tonne CO_2 in 2030, indicating that a strong climate policy is required to enable zero-emission trucks to become competitive. In Net-Zero, Global Action, plug-in hybrid sales increase to 19% from 2030-2035 and begin to decline in later periods, suggesting that these trucks may be a bridging technology on the pathway to net zero. They are a cheaper solution than BEVs or hydrogen trucks while the carbon price is low and produce fewer emissions than diesel trucks. Once the carbon price becomes high, PHEVs would slowly transition out of the market, making way for fully zero-emission trucks.

New Market Share of on-road freight trucks in Net-Zero, Global Inaction can be found in Appendix B. The key difference is the extent to which flex-fuel trucks dominate, winning

79% of New Market Share, while BEV take 8%, PHEV take 7%, and diesel trucks take 6%. In Global Inaction, flex-fuel trucks run on B100 and diesel trucks run a blend of B20. Flex-fuel trucks earn more sales in Global Inaction because capital costs for battery electric trucks fall at a slower rate due to their lower AEEI, making electric trucks less competitive. Once again, there are negligible sales of hydrogen trucks, perhaps only in a few niche market situations.

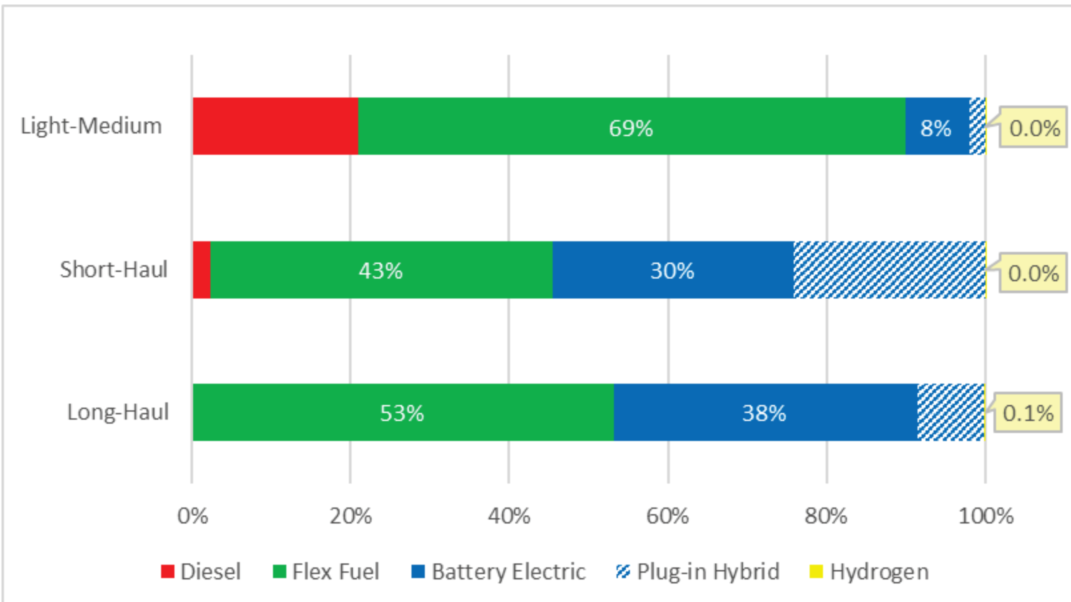
Again, it is important to note that as a particular form of energy, such as biodiesel, rapidly increases market share, the model does not produce a corresponding change in the price of that commodity. This is a shortcoming of the model design I have used in that it neglects some of the countervailing effects observed in real-world markets.

Figure 9: New Market Share for Freight Trucks under Net-Zero, Global Action



When comparing trucks to assess whether mode affects the contribution of each zero-emission truck to a zero-emission road freight sector, I analyzed data from Net-Zero, Global Action. In Net-Zero, 69% of Light-Medium Motors are flex-fuel trucks consuming B100 and 21% are diesel trucks consuming B20. The remaining 10% of sales are BEVs and PHEVs. In Short-Haul Heavy Motors, 43% of new trucks are flex-fuel trucks consuming B100, 30% are BEVs and 24% are PHEVs. Only 2% of new short-haul trucks are diesel engines consuming B20. In Long-Haul Heavy Motors, 53% of new sales are flex-fuel trucks consuming B100, 38% are BEVs, 9% are PHEVs and no conventional diesel trucks are sold by 2050. *Figure 10* depicts New Market Share in each truck mode in Global Action. Flex-fuel trucks prevail as the dominant zero-emission truck in each mode, but the degree to which flex-fuel dominates seems to be influenced by truck mode. Light-medium trucks favor flex-fuel over electric options, while heavy trucks (in both long and short-haul) see a more even spread between flex-fuel and electric trucks. Furthermore, diesel trucks seem to remain a larger portion of the trucking industry for light-medium trucks, while they are almost completely phased out for heavier trucks.

Figure 10. New Market Share in 2050 by Truck Mode in Net-Zero, Global Action



The difference in New Market Share between truck modes may seem counterintuitive. Typically, transport experts predict that electricity may be preferred for light-medium trucks due to shorter ranges and more opportunity to recharge batteries throughout the day. Likewise, many experts assume hydrogen or flex-fuel trucks have a greater chance to dominate heavy, long-haul trucking because of the range restrictions from batteries in BEVs. Yet, my Net-Zero forecast indicates that New Market Share for light-medium trucks may be dominated by flex-fuel trucks rather than BEVs, and heavy trucks will see an even spread of flex-fuel and electric trucks.

The Life-Cycle Cost (LCC) of each truck helps explain this counterintuitive trend. In trucking, the LCC is measured in dollars per tonne kilometer travelled ($/TKT) and includes capital, operating, fuel, and infrastructure costs. *Figure 11* shows the LCC of Light-Medium Motors under Net-Zero, Global Action. In light-medium trucks, zero emission technologies are more expensive than diesel until 2035 when the carbon price causes the LCC of diesel trucks to increase above zero-emission technology options. By 2050, flex-fuel trucks cost $0.45/TKT which is the cheapest truck on the market, giving them a clear cost advantage on the pathway to zero-emission in light-medium trucks. From 2020 to 2050, hydrogen truck costs fall $0.12/TKT and electric truck costs fall further at $0.16/TKT, but both fail to achieve cost parity with flex-fuel trucks, allowing flex-fuel trucks to dominate.

Figure 11. Cost per TKT for Light-Medium Motors

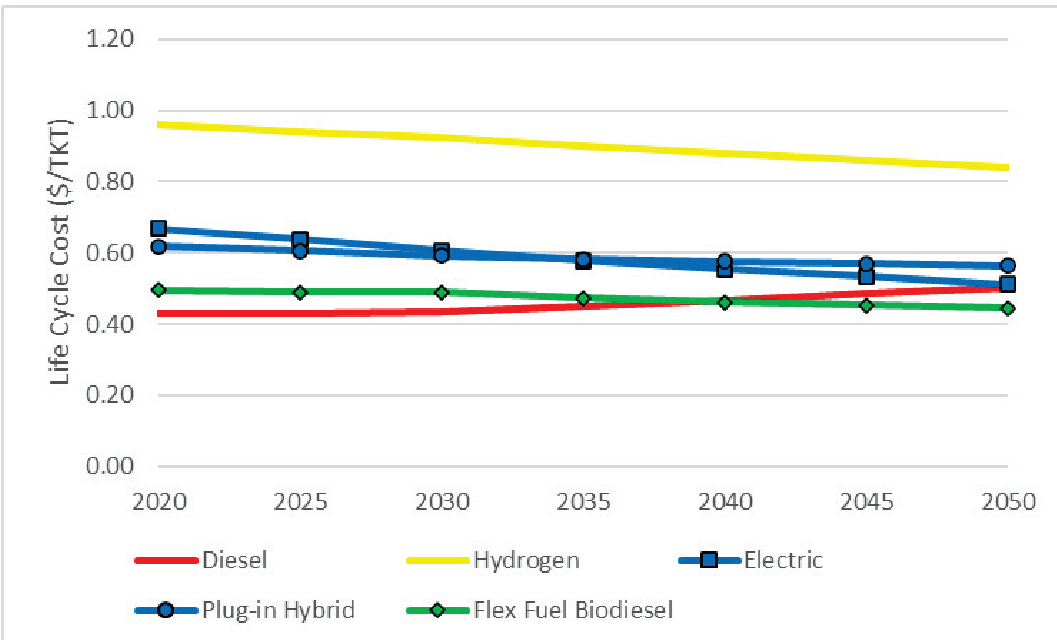


Figure 12 shows the LCC for Short-Haul Heavy Motors. In this mode, the cost for diesel trucks starts to rise in the 2030-2035 period because of the rising domestic carbon tax which eventually gets so high that it is more than compensating for the lower oil price in the Global Action scenarios. In 2050, flex-fuel trucks are the cheapest truck on the market at $0.21/TKT. BEV and PHEV trucks both cost $0.22/TKT to operate which is close enough to flex-fuel truck costs that they begin to enter the market in larger numbers. Hydrogen trucks fail to enter the market because their life-cycle costs are considerably higher than all other truck technologies. All short-haul heavy trucks have a smaller LCC compared to their light-medium counterparts because light-medium trucks accumulate the fewest TKT, so their $/TKT value will be higher compared to trucks that accumulate more TKT due to heavier loads and further distances travelled.

Figure 12. Cost per TKT for Short-Haul Heavy Motors

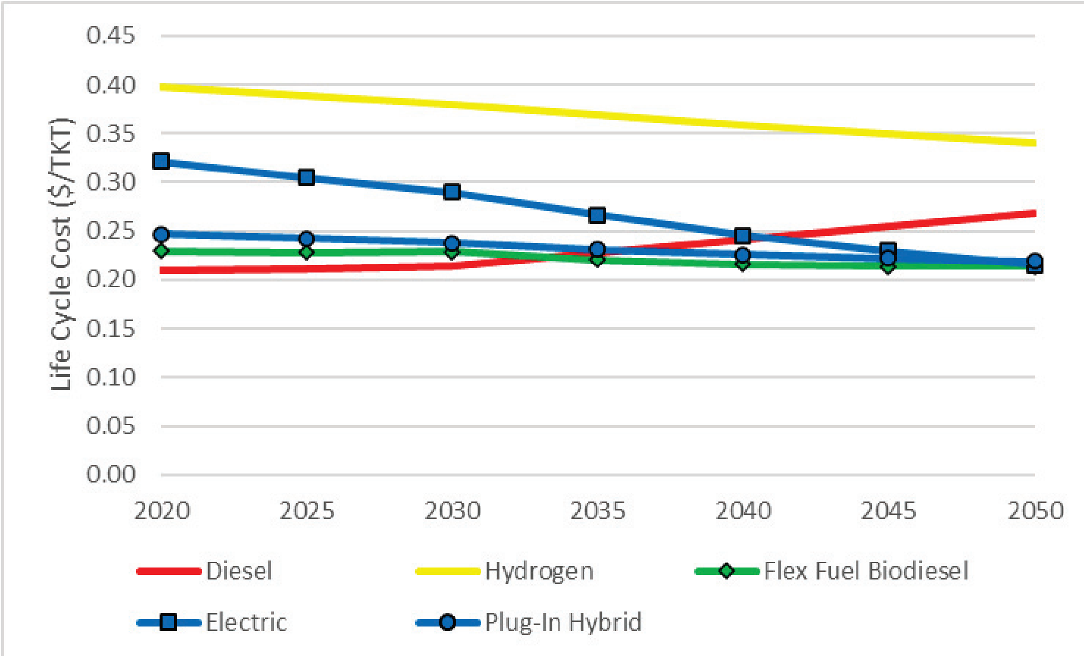
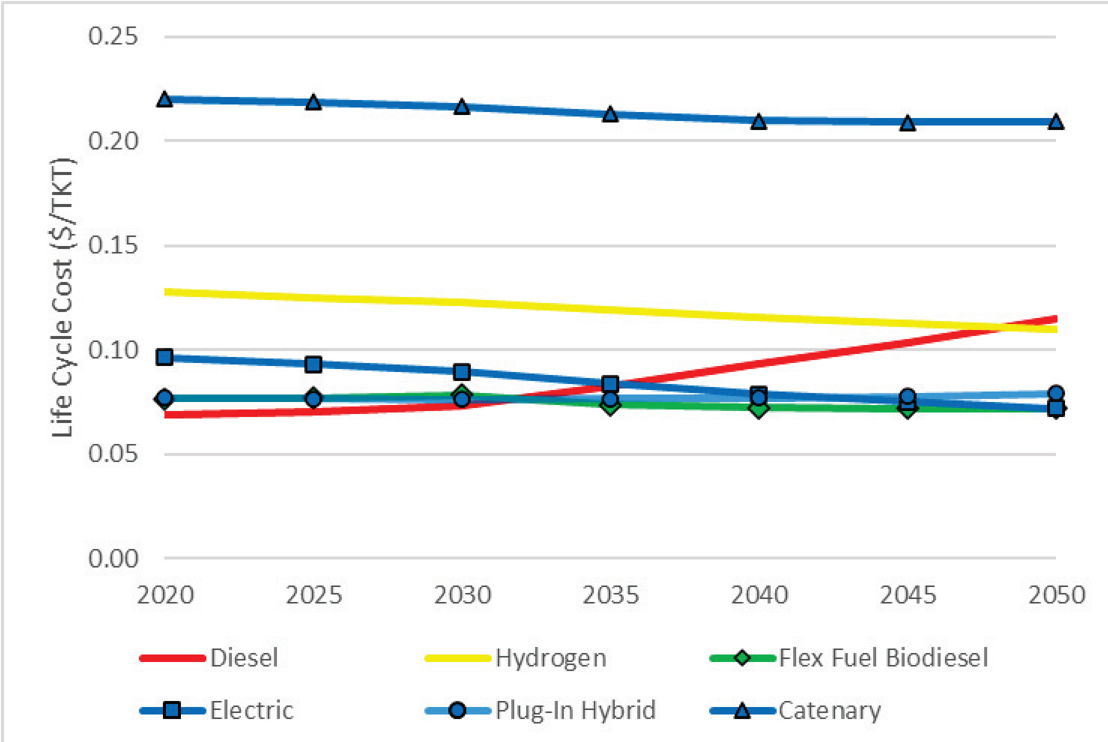


Figure 13 depicts the LCC for Long-Haul Heavy Motors. The LCC of all zero-emission trucks remains higher than diesel until the 2030-2035 period. Beyond 2035, each zero-emission truck (excluding hydrogen) becomes cheaper than diesel, thereby eliminating diesel sales. Flex-fuel and plug-in hybrid trucks cost the same until 2035 when PHEVs become more expensive, allowing flex-fuel trucks to dominate the market. By 2050, flex-fuel and electric truck costs have both fallen to $0.07/TKT, while PHEV are $0.01 more expensive, resulting in New Market Share being divided between flex-fuel and electric trucks. Hydrogen trucks are cheaper than diesel by 2050 but never cost-competitive with other zero-emission technologies. Catenary trucks remain two times more expensive than flex-fuel trucks by 2050, so they never enter the market. Long-haul heavy trucks have the lowest LCC because they accumulate the most TKT due to long hauls, with heavy payloads.

Figure 13. Cost per TKT for Long-Haul Heavy Motors



The low LCC of long-haul motors compared to the high LCC of light-medium motors helps to explain the reason why flex-fuel trucks dominate in light-medium, while BEVs and flex-fuel trucks capture a more even spread of New Market Share for long-haul trucks. For instance, even when capital costs for long-haul electric trucks are 132% more expensive than flex-fuel trucks, life-cycle costs need to only fall $0.03/TKT to reach cost parity with flex-fuel trucks. In light-medium, electric trucks costs must fall $0.22/TKT, thus costs must fall further to reach cost parity with the winning truck. In both modes, electric trucks will not enter the market until they are cost competitive, but because electric long-haul motor costs are so close to flex-fuel truck costs, the rising carbon price and technological advancements from other jurisdictions push long-haul trucks to cost parity faster than light-medium.

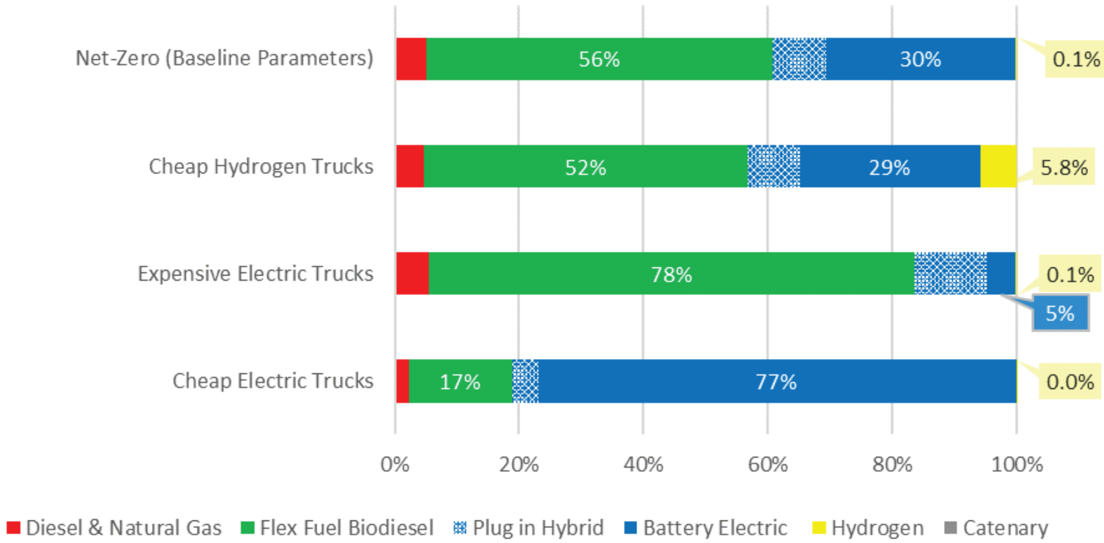
Again, it is important to note that these particular results could change significantly with just small changes in how I simulated markets. For example, had I included a rising cost curve for the biomass inputs to produce biodiesel, the shift to this option might not have materialized. Instead, electricity and perhaps even hydrogen might have dominated the market. Even hydrogen domination might be possible, especially if the domestic supply curve for zero-emission production of electricity were also deemed to be steep due to the higher costs of dramatically expanding reliable zero-emission generation (with nuclear and large hydro perhaps blocked).

4.3. Vehicle Cost Simulations

In the vehicle cost simulations, I altered truck capital costs within the range of reported uncertainty to forecast how different values of this key variable on their own might affect the likely contribution of each zero-emission technology in the road freight sector. Each simulation was run under both scenarios and then compared to Net-Zero which represented the baseline technological parameters. In these simulations, every technological variable, other than the capital costs of zero-emission tucks, was held constant. In this section, I present results for eight of the ten vehicle cost simulations. I omitted the results from Expensive Hydrogen Trucks in both scenarios because results are identical to the other Net-Zero results and therefore provide no additional value.

Given my assumptions, flex-fuel trucks win the market by 2050 in six simulations. Flex-fuel trucks win New Market Share in Net-Zero, Expensive Electric Trucks, and Cheap Hydrogen Trucks under Global Action and Inaction. In all vehicle cost simulations, flex-fuel trucks run solely on B100. Given that flex-fuel trucks win New Market Share when applying baseline electric truck costs, flex-fuel trucks win by an even greater margin when electric trucks are more expensive, with up to 87% of sales. In Expensive Electric Trucks, electric truck sales plummet to 5% in Global Action and 0% in Global Inaction as the cost of electric trucks is too high to be competitive. In Cheap Hydrogen Trucks, flex-fuel trucks continue to dominate, but to a lesser degree as 2% to 6% of sales are hydrogen trucks. In two simulations, flex-fuel is outcompeted by electric trucks, with flex-fuel truck sales falling as low as 17%. Electric trucks win New Market Share in the Cheap Electric Truck simulation with 77% of sales in Global Action and 54% in Global Inaction. Electric truck sales are higher in Global Action because climate mitigation in other jurisdictions drives capital costs down faster for electric trucks due to economies-of-scale and economies-of-learning. Thus, electric trucks in Canada can capture more New Market Share. A summary of New Market Share contributions under the vehicle cost simulations for Global Action can be found in *Figure 14*. Appendix B presents the results for vehicle cost simulations under Global Inaction.

Figure 14. New Market Share for All Vehicles in 2050 under Vehicle Cost Simulations



From the vehicle cost simulations, we can see that uncertain capital costs may influence the contribution of each zero-emission vehicle to a decarbonized road freight sector – but to varying degrees. Hydrogen truck costs are uncertain with cost estimates within $257,000 of each other yet altering truck cost did not tip the market in favor of hydrogen, suggesting that New Market Share is insensitive to hydrogen truck cost alone. For hydrogen trucks to become competitive, truck costs may need to fall even further than current low estimate predictions through extensive research, development, and innovation, or climate policy could enforce the use of hydrogen trucks over other technology options, or low truck costs must be associated with high costs for trucks and energy used by the zero-emission competitors to hydrogen.

Electric truck costs are also uncertain, with costs ranging as much as $248,000, but when altering costs within this range, a tipping point exists that pushes the market towards flex-fuel or electric trucks. The shifts in truck sales that occurred as I altered electric truck costs suggest that New Market Share is likely sensitive to the cost of electric trucks. Therefore, for electric trucks to potentially become competitive a stringent climate policy must be in place and the price of electric trucks must be on the cheaper end of the uncertainty range which can be achieved through targeted development of electric truck technologies to ensure cheaper capital costs.

Life-cycle costs for each truck mode suggest that Light-Medium Motors are most sensitive to vehicle cost. In electric trucks, 80% of the LCC was from capital costs for Light-Medium Motors, 68% for Short-Haul Heavy Motors, and 52% for Long-Haul Heavy Motors. Light-Medium Motor sales shifted more than in other modes because of the high capital cost contribution to the LCC of light-medium electric trucks. Appendix C provides the LCC contributions for each zero-emission truck in all modes. For Light-Medium Motors, a 10% decrease in capital costs, on average, increased electric trucks sale by 21%. While the same 10% decrease in cost only increased Short-Haul Heavy Motor sales by 15% and Long-Haul Heavy Motors by 11%. Hydrogen trucks followed the same trend with most new sales coming from light-medium trucks when costs were low.

4.4. Energy Cost Simulations

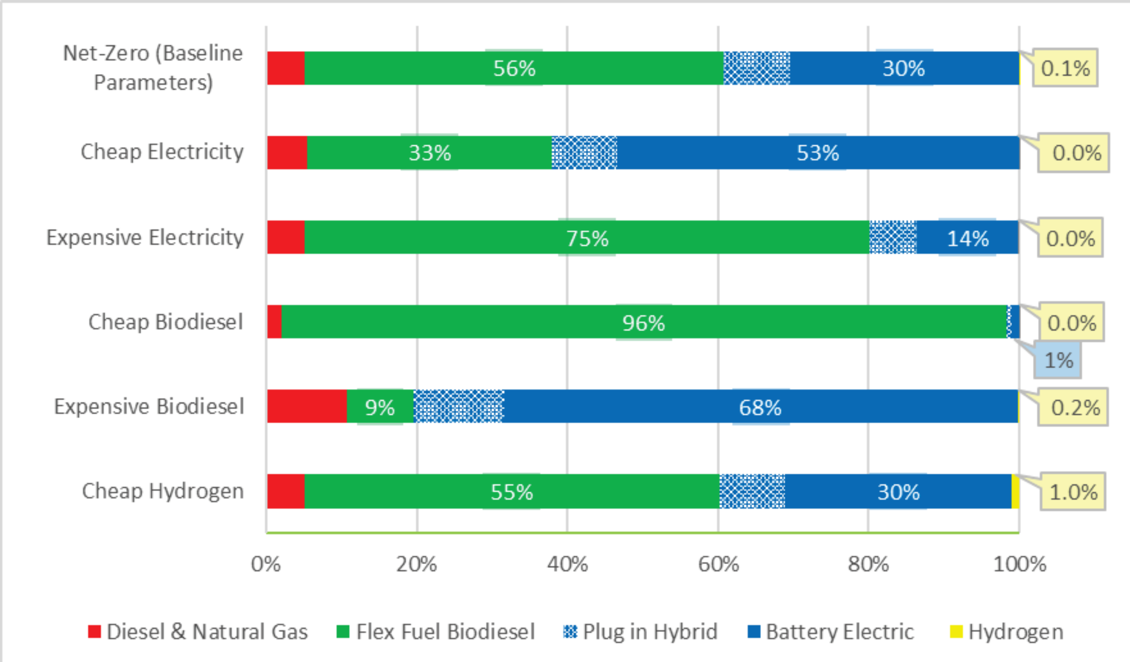
I ran 12 simulations to examine how energy costs alone influence the market share of zero-emission vehicle technologies by comparing each simulation to Net-Zero which represents the baseline technological parameters. Each energy cost simulation had either a cheap or expensive hydrogen, biodiesel, or electricity cost based on estimates from literature. Each simulation was run under Global Action and Global Inaction. I omitted the results from Expensive Hydrogen in both scenarios because results are identical to the Net-Zero simulation and therefore, provide no additional value.

Given my assumptions, flex-fuel trucks win the market in nine of the 12 simulations. Flex-fuel trucks win New Market Share in Net-Zero, Expensive Electricity, Cheap Biodiesel, and Cheap Hydrogen in both scenarios. In all energy cost simulations, flex-fuel trucks run solely on B100. In Net-Zero, flex-fuel trucks win 55% of sales in Global Action and 79% of sales in Global Inaction. When electricity is more expensive (Expensive Electricity), flex-fuel trucks dominate to an even greater extent, capturing 75% of New Market Share in Global Action and 88% in Global Inaction. When biodiesel costs are at their lowest estimate (Cheap Biodiesel), flex-fuel trucks capture almost the entire market with 96% to 97% of sales depending on scenario. When hydrogen costs fall (Cheap Hydrogen), hydrogen truck sales are still negligible, never surpassing 1%. The final simulation in which flex-fuel trucks win the market is when electricity cost is cheap (Cheap Electricity), and the world fails to act on climate change (Global Inaction). In this simulation, flex-fuel trucks win 59% of sales.

In Cheap Electricity under Global Action, electric trucks win 53% of New Market Share. In all other simulations, the level of GHG mitigation effort only affects the extent to which a truck wins, but the cost of electricity coupled with the level of GHG mitigation effort may affect which truck technology wins the market. Electric trucks also beat out flex-fuel trucks when biodiesel is expensive (Expensive Biodiesel), capturing 68% of sales in Global Action. In Expensive Biodiesel, Global Inaction, electric trucks capture most New Market Share, but do not win the market as they only earn 43% of new sales, while flex-fuel trucks earn 15%. In this simulation, 28% of sales comes from PHEVs which further suggests that battery electric trucks fail to control the market in a world where countries fail to act on climate change.

From the energy cost simulations, we see that uncertain electricity and biodiesel costs are likely to influence the contribution of each zero-emission vehicle to a decarbonized road freight sector. Electricity costs ranged from $22.69 to $42.15/GJ in 2050, and as costs shifted from cheap to expensive, New Market Share of electric trucks shifted from 53% to 2%. Electricity cost was the most certain of the energies examined due to a larger scale of zero-emission electricity commercialization, yet New Market Share shifted drastically enough that the winning technology changed depending on electricity costs. Biodiesel costs ranged from $12.46 to $53.46/GJ in 2050 which caused New Market Share to increase to 97% and decrease to 9%, suggesting that future biodiesel cost will likely influence the makeup of the road freight sector. Hydrogen cost, on the other hand, appears unlikely to shift the contributions of zero-emission trucks as New Market Share barely shifted even as fuel cost ranged from $15 to $51/GJ in 2050. The summary of New Market Share contributions for all vehicles under energy cost simulations for Global Action are in *Figure 15.* Global Inaction results can be found in Appendix B.

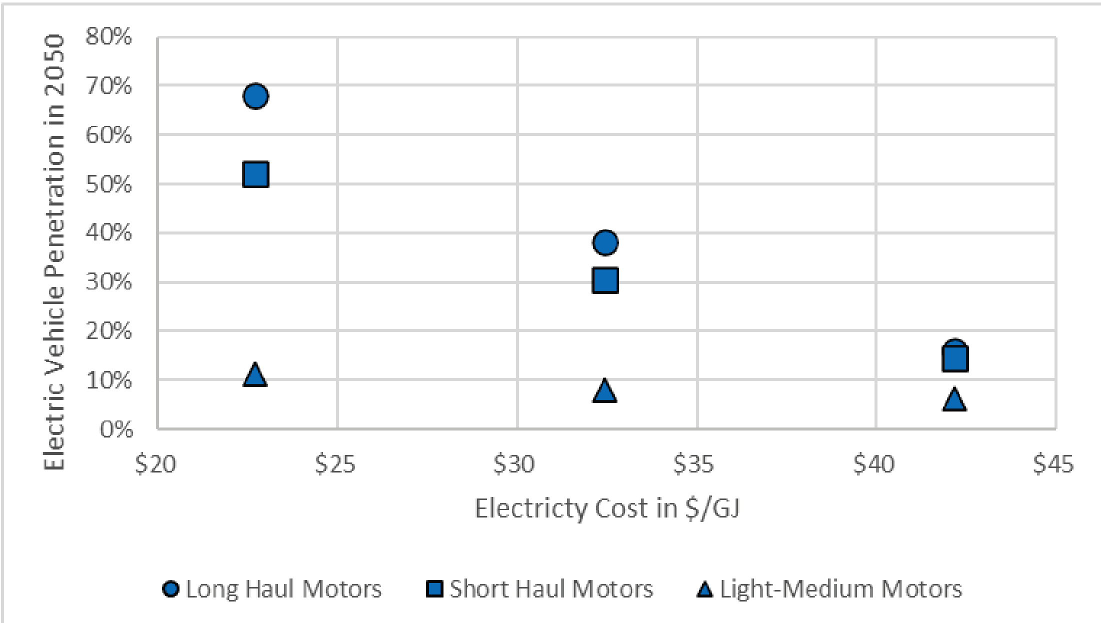
Figure 15: New Market Share for All Vehicles in 2050 under Energy Cost Simulations



Based on the New Market Share of each truck mode, Long-Haul Heavy Motors are most sensitive to the cost of energy. This is because energy costs comprise a larger portion of the LCC for long-haul motors compared to short-haul or light-medium. For example, in electric trucks, energy costs make up 26% of long-haul heavy life-cycle costs, 9% of short-haul heavy, and 5% of light-medium. As a result of these different contribution levels, every $10/GJ decrease in electricity cost increases long-haul motors sales by an average of 27%, short-haul by 19%, and light-medium by only 3%.

Figure 16 shows the 2050 relationship between electricity cost and electric truck New Market Share for each truck mode. It shows that energy costs cause the greatest range in result for New Market Share in Long-Haul Heavy Motors, followed by Short-Haul Heavy Motors, then Light-Medium Motors. Representatives of the road freight industry sometimes suggest that zero-emission long-haul trucks are still in early stages of development, but my results suggest that lack of strong climate policy could block the market success of these alternatives indefinitely. Governments can alleviate industry concerns by assisting in the transition to zero-emission long-haul trucks by focusing research and development on energy costs as they make up such a large portion of life-cycle costs. But strong GHG pricing and technology regulations appear to be critical in causing a transition to zero-emission road truck freight transport in just a few decades. Appendix D compares fuel cost with zero-emission vehicle penetration for hydrogen and flex-fuel trucks; both these trucks follow the same trend for each mode with Long-Haul Motors being the most sensitive to energy costs.

Figure 16. Electricity Cost vs. Electric Truck New Market Share 2050



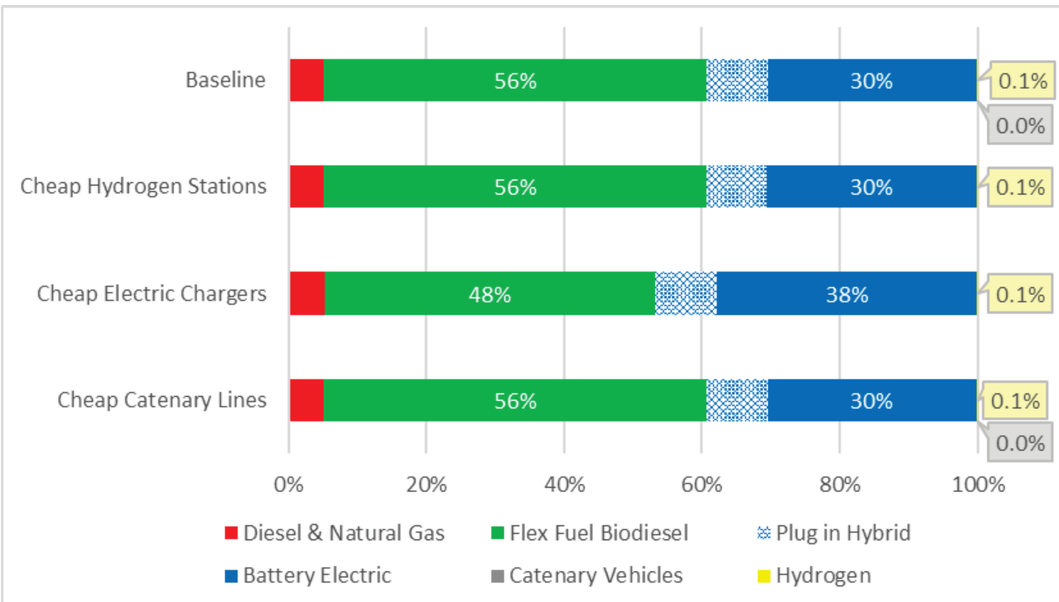
4.5. Infrastructure Cost Simulations

I ran six simulations to examine how changes in infrastructure costs alone might influence the market share of zero-emission vehicle technologies by comparing each simulation to Net-Zero, which represents the baseline technological parameters. I ran a cheap simulation for hydrogen refueling stations, electric chargers, and catenary lines under both scenarios.

Flex-fuel trucks that run solely on biodiesel win New Market Share in every infrastructure simulation. As already mentioned, flex-fuel trucks win 56% of sales in Net-Zero under Global Action and 79% under Global Inaction. When I applied the cheap estimate to the Cheap Hydrogen Stations and Cheap Catenary Lines simulations, New Market Share for each truck did not shift in either Global Action or Inaction. Because market share did not change, even when costs fall over 40% for both infrastructure types, we can predict that infrastructure costs for hydrogen and catenary trucks are unlikely to influence by themselves the contributions of zero-emission trucks to the road freight sector.

In the Cheap Electric Chargers simulation, flex-fuel trucks still win the market, but to a lesser degree. In Global Action, 8% of sales switch to electric trucks and in Global Inaction, 3% of sales switch. In this case, infrastructure cost affects the likely contribution of zero-emission trucks, but not in a way that influences which truck will dominate in the road freight sector. *Figure 17* shows the level of contribution for all trucks under infrastructure simulations for the Global Action scenario, while Appendix B shows the results for Global Inaction.

Figure 17: New Market Share for All Vehicles in 2050 under Infrastructure Costs Simulations



Electric trucks see a shift in New Market Share, in comparison to hydrogen trucks because charging stations make up a larger percent of the life-cycle costs of electric trucks. For example, in Long-Haul Heavy Motors, charging stations contribute 9% to electric truck life-cycle costs while hydrogen refueling stations only contribute 6% towards hydrogen truck life-cycle costs. Therefore, changes to infrastructure cost may have a larger impact on New Market Share for electric trucks.

Catenary trucks, on the other hand, see most of their life-cycle costs come from the cost of catenary lines, contributing 72% of the life-cycle cost. In this case, the upfront capital cost is too high to allow catenary trucks to become affordable, even with an estimate 40% cheaper than baseline.

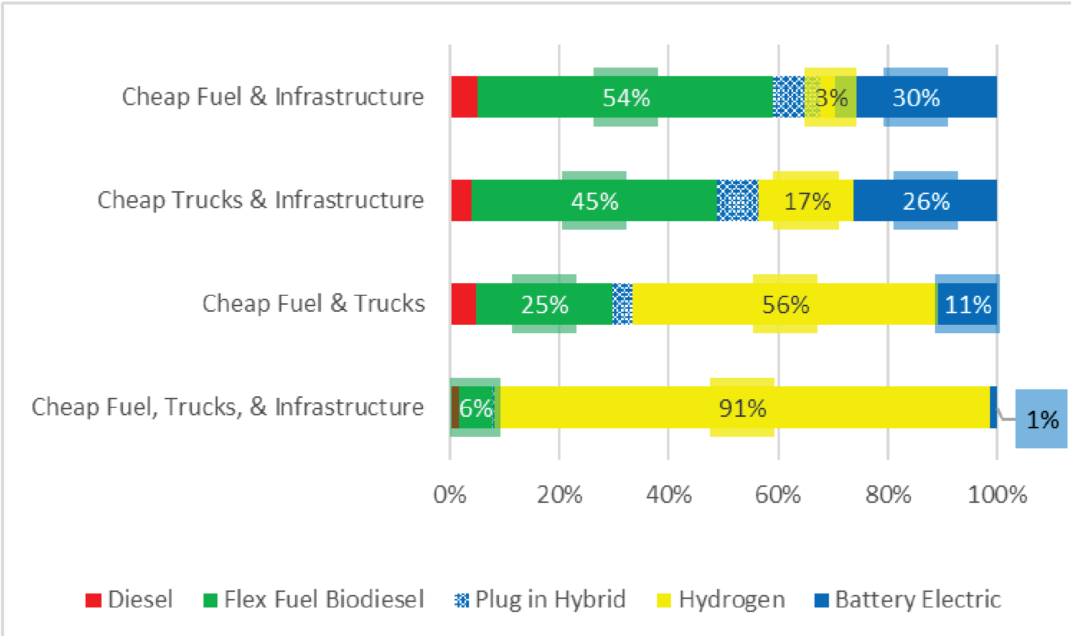
Finally, it is important to note that in general change in infrastructure cost by itself does not seem to influence New Market Share because low LCC contributions mean that even cheap costs do not tip the market towards one technology over another. This result is important for decision makers – often the transition to zero-emission trucks is delayed due to concerns about the high cost of infrastructure, but my results suggest that infrastructure costs will not influence New Market Share. A tipping point may exist where an even lower cost for infrastructure would shift the likely contributions of zero-emission trucks to the road freight sector, but as of today, dramatically lower costs don't seem likely.

4.6. Extra Simulations

After reviewing all the simulations showing the unlikeliness of hydrogen market domination, I decided to run four additional simulations to determine if a combination of favourable cost and price estimates might create a tipping point for hydrogen's New Market Share in 2050. In these simulations, I paired the cheapest cost parameters for hydrogen fuel, trucks, and infrastructure to create three simulations: Cheap Fuel & Infrastructure, Cheap Fuel & Trucks, and Cheap Trucks & Infrastructure. Finally, I ran a simulation with all three hydrogen parameters at their cheapest potential value (Cheap Fuel, Trucks, & Infrastructure). I did not run these simulations under Global Inaction as this scenario naturally hinders hydrogen truck adoption, and I was seeking to find potential futures where hydrogen is successful.

Figure 18 shows the results for these extra hydrogen-focused simulations. Hydrogen trucks win the market in two simulations. In Cheap Fuel & Vehicle, hydrogen trucks win 56% and in Cheap Fuel, Vehicle, & Infrastructure, they win 91% of sales. Under my assumptions, pairing cheap fuel or truck costs with cheap infrastructure costs (Cheap Fuel & Infrastructure and Cheap Trucks & Infrastructure) is still not enough to shift the balance of the market in favor of hydrogen trucks.

Figure 18: New Market Share for All Freight Trucks when Altering Multiple Hydrogen Parameters



The extra simulations show that it is possible for hydrogen trucks to win the market, but concerted innovation effort would likely need to be pursued to ensure that truck and fuel costs both achieve low-cost estimates or government could implement targeted regulations to ensure hydrogen truck penetration. These types of strategies would benefit hydrogen truck adoption but are. not needed because other zero-emission trucks are able to enter the market, replacing diesel trucks and achieving GHG emission reductions of 70% from 2000 levels in the process.

Again, however, it is important to note that my partial equilibrium version of the CIMS model may be considered too optimistic by some experts on the energy prices of hydrogen’s biodiesel and electricity competitors as these options gain market share. It may turn out that biofuel supply is significantly constrained in future and even modest increases in its use will lead to extremely high prices for biodiesel. It could also turn out that hydrogen production will increasingly benefit on a net-zero trajectory from the extremely low cost of non-dispatchable solar and wind electricity that, via electrolysis, could be used to produce hydrogen while hydrogen storage on vehicles and in refueling / recharging stations proves cheaper than electricity storage.

Chapter 5. Conclusion

In this final chapter, I review key insights from my analysis, identify some of its limitations and thus avenues for future research, and provide a summary.

5.1. Insights

First, it is possible to achieve 70% GHG emission reduction by 2050 from 2000 levels. One frequently hears that trucking emissions will be difficult to abate because zero-emission trucks are in early stages of development and costs must fall before climate policy will be effective. As in every sector of the economy, the higher cost of zero-emission technology is not a reason for delay. A rapidly rising carbon price and/or equivalent technology and energy regulations that reflect the environmental and social costs from the GHG emissions of conventional trucks will lead to technology and energy substitution. Moreover, as they penetrate the market, these fledgling zero-emission technologies will experience economies-of-scale and economies-of-learning that reduce their costs.

Second, uncertain technological parameters will likely influence the New Market Share of the road-freight sector on its path to zero-emissions, to varying degrees. New Market Share seemed most sensitive to electricity and biodiesel costs, as well as electric truck costs. When altering these three parameters, new market share tipped in favor of flex-fuel trucks or electric trucks. Policymakers could develop strategies to innovate electricity, biodiesel, or electric truck production to help ensure costs are lower, but innovation is not essential. The rising carbon price achieves emission reduction without explicitly targeting innovation, but research and development support could be applied in concert with the rising carbon price to help industry generate and adopt innovations to accelerate cost declines.

Third, my modelling results derived from my assumptions suggest assumptions suggest that hydrogen trucks are unlikely to become a key competitor in the road freight sector, unless government intervenes, or concerted innovation effort occurs. Hydrogen trucks did not win the market in any simulation I conducted until I assumed cheap estimates for multiple hydrogen-related parameters. If a government decided that hydrogen trucks were superior to other zero-emission truck options (for non-financial reasons), regulatory policies such as zero-emission vehicle mandates could be implemented that only allow for hydrogen trucks. Governments could also provide funding grants to improve hydrogen trucking technologies over other zero-emission options, and to support the development of hydrogen distribution and refueling infrastructure. To enforce a hydrogen future is possible, but governments should be wary of such a targeted strategy if other zero-emission options are available and might prove more desirable to market participants for various reasons. But, as with all of my results, the negative outcome for hydrogen may be altered if assumptions about the future potential for low-cost biodiesel and/or reliable electricity are adjusted to reflect significantly rising prices with greater adoption and expansion.

Fourth, New Market Share appears to always be insensitive to the cost of infrastructure. Sometimes the cost of infrastructure is depicted as a barrier to adoption, but my simulations indicate that even aggressively low costs may not influence the likely contributions of each type of zero-emission truck. However, while the cost of infrastructure may not be a key barrier once installed, it remains a barrier because of the major upfront investment required to achieve a certain threshold. This is sometimes referred to as the “lumpy investment” or “chicken and egg” problem. A hydrogen refueling system involves a massive investment that is only recompensed if there are a lot of hydrogen trucks whose hydrogen purchases pay the capital costs. But consumers and producers of trucks will not venture strongly into hydrogen vehicles until such refueling infrastructure is ubiquitous. Similarly, installing catenary wires along a truck route is a massive investment that will also see insufficient users for a lengthy period after construction. In summary, firms will not purchase these types of trucks because there is no infrastructure to support them, but infrastructure will not be installed because there are no trucks on the road that will use it. Trucking firms, external infrastructure suppliers, and governments should work together to ensure that infrastructure rollout meets the refueling requirements of new zero-emission trucks as climate policy is strengthened.

Fifth, of the range of trucking modes examined, long-haul trucks are most sensitive to energy costs because they drive the furthest and are the heaviest. This means that energy is a larger percentage of life-cycle cost compared to other vehicle modes. As a result, when energy cost increases or decreases, sales of long-haul motors changes most substantially. Knowing that long-haul motors are sensitive to energy costs is important for decision makers. Long-haul motors are typically considered the hardest truck mode to transition to zero-emission motors because of their heavy payloads and long-hauls that can cause range anxiety with the zero-emission alternatives that lack an adequate refueling / recharging infrastructure. However, my study suggests that (1) long-haul trucks can transition away from diesel with a stringent enough carbon price and (2) innovation can be targeted towards energy production methods which will reduce LCCs and hopefully transition long-haul trucks to zero-emission more seamlessly.

Sixth, long-haul and short-haul motors behave similarly on the path to decarbonization. Under each simulation, I discovered that (1) the winning technology in each mode was the same for each simulation and (2) the extent to which the technology is the winner changes only slightly depending on the mode. Past research has stressed the need to disaggregate the road freight sector to better represent the heterogeneity of trucks (Hammond et al., 2019; Lajevardi et al., 2019). My research provides a disaggregated analysis of the road freight sector, but under the assumptions I tested this disaggregation did not seem consequential. Perhaps it would be with even greater disaggregation or different assumptions.

Seventh, the lightest freight trucks are more challenged in transitioning away from conventional diesel relative to larger, heavier trucks. The life-cycle cost of each zero-emission truck must reach cost parity with diesel trucks to become competitive in the market. Some light trucks become competitive between 2040 and 2045 when flex-fuel truck costs have fallen $0.03/TKT. Heavy trucks, on the other hand, become competitive 10 years earlier when flex-fuel truck costs have fallen $0.01/TKT. Light trucks take longer to reach cost parity because costs must fall further than for heavier trucks, thus slowing the rate of adoption. This slower transition resulted in diesel making up 21% of new truck sales in 2050. The capital cost of lighter trucks was the most substantial component of life-cycle cost, so targeted innovation to reduce the costs of parts needed for zero-emission trucks would help ensure that all truck modes adopt zero-emission energy options.

Finally, the level of global mitigation I assumed affects the likely contribution of each vehicle. In a Global Inaction scenario, when flex-fuel trucks win the market, they do so with over 60% of sales in each of my simulations. In Global Action, on the other hand, there is a more even spread between flex-fuel and electric trucks, with flex fuel winning the market by a smaller margin. In only one of my simulations does the level of global action change the winning technology; under Cheap Electricity, electric trucks win in Global Action, while flex-fuel trucks win in Global Inaction. The difference between Action and Inaction highlights the role the rest of the world plays in Canada's on-road freight sector. Without a global effort, emerging technologies, such as electric and hydrogen trucks, struggle to properly develop.

5.2. Limitations and Future Research

A limitation of my study is the lack of data in the road freight sector on intangible costs which reduces the behavioral realism of my forecasts. Literature suggests that, in general, firms' decision will be more financial-cost driven than is the case with some individual consumers by purchasing the technology with the lowest life-cycle costs. However, limited research has specifically focused on how trucking firms make technology-acquisition decisions, and how specific types of risks of new zero-emission technologies will be perceived and weighted. The lack of intangible costs may be especially relevant to electric long-haul trucks. In my forecasts, long-haul electric trucks were a large portion of New Market Share in multiple simulations, but most experts agree that electric trucks are not a viable option in long-haul trucking due to range limits and refueling challenges. I chose to omit intangible costs because any value I inputted would not have had research to support it. Future research might estimate and then add intangible costs to trucking technologies.

Another major limitation of my study was that I conducted only single variate sensitivity analysis by altering one uncertain variable at a time from the baseline assumption. This allowed me to understand how each uncertain variable influences new market share of zero-emission trucks while other variables are held constant. However, it is possible that multiple variables would shift to cheap or expensive at the same time. For instance, advancements in electric charging stations may spur rapid innovation in electric trucks, achieving my lowest cost estimate for both. Multivariate sensitivity analysis can be conducted in future research to understand the likely contribution of zero-emission technology given multiple uncertain variables acting in tandem. I did this to a limited extent by looking at my initial results and then conducting multiple uncertainty analyses to explore the conditions under which hydrogen might win.

Another limitation was that my version of CIMS does not currently represent the biodiesel sector as fully as might be helpful. In my model, conventional biodiesel (with a 20% blend limit) and advanced biodiesel (with no blend limit) were combined into one fuel. Because I could not determine whether biodiesel sold in Canada was conventional or advanced, I had to restrict all diesel trucks to a 20% blend limit and add a flex-fuel truck to allow for higher blends. But, in the real world, higher blends are possible in existing trucks when using advanced biofuels like renewable diesel. Furthermore, in simulations where I included a carbon price to achieve 70% emission reduction, conventional trucks used B20, but it is possible that this blend would be higher if I had allowed it. If CIMS were altered so that conventional biodiesel was separate from advanced biodiesel, diesel trucks could use a blend higher than B20 and it is possible that the pathway to a zero-emission road freight sector would not require new zero-emission trucks. Instead, freight operators could keep using their existing trucks, but fuel them exclusively with advanced biofuels.

Finally, because my version of the CIMS model was partial equilibrium with respect to (1) some aspects of domestic energy production like biodiesel and its supply curve, and (2) macro-economic feedbacks, particularly the effect of transport cost on the demand for road freight transport, my simulation of the response to carbon pricing and other GHG-reducing policies may be incomplete and potentially misleading. Two potential problems stand out. First, while biodiesel took over the market in many of my net-zero simulations, my model lacked a feedback by which the price of biodiesel might rise as more biomass is sought from a fixed landmass. This could have profound implications for the market share results. Second, while the cost of goods transport rose with the rising carbon price and substitution from low-cost (high emission) conventional diesel trucks to zero-emission (higher cost) alternatives, the demand for goods transport should decline to some extent, thus making the reduction target easier to achieve. This means that my estimate of only a 70% GHG reduction from this sector at a carbon price over $1000 may be inaccurate. It could be that a much lower carbon price would achieve a much higher percent reduction in road freight transport emissions.

5.3. Summary

The purpose of my research was to gain insight on the likely contributions of zero-emission technologies to a dramatically decarbonized road freight sector by conducting sensitivity analysis on uncertain technological parameters and global mitigation efforts. Using CIMS, a partial equilibrium, energy-economy-emissions model, I ran numerous simulations with different assumptions about capital costs for vehicles, infrastructure costs, and energy costs over a 30-year period under two different scenarios: Global Action and Global Inaction. CIMS was my model choice as it allowed for various end-use technologies to compete with one another, enabling me to understand the likely contributions of each cost element of each vehicle to a decarbonized road freight sector.

I ran a BAU simulation where the carbon price did not increase, compared with all other scenarios where the carbon price increased to achieve 70% emission reduction. I modeled 26 distinct trucks identified as Light-Medium, Long-Haul Heavy, and Short-Haul Heavy – each relying on a certain fuel and infrastructure to operate. The primary output examined was New Market Share for various types of trucks in 2050, and I also reported on GHG emissions and life-cycle costs of each truck.

From the 24 original simulations, flex-fuel trucks win the market in 19, electric trucks win in five, and hydrogen always fails to achieve more than 6% of sales, even by 2050. New Market Share ranged widely for flex-fuel and electric trucks, depending on the simulation. For flex-fuel trucks, sales fell as low as 9% and as high as 97%. Electric truck sales stayed negligible in some simulations but achieved as high as 77% in others. Because hydrogen failed to attain market dominance when varying single uncertain factors, I then ran four extra simulations to determine if hydrogen could become competitive when combining cheap estimates for hydrogen trucks, fuels, and infrastructure. In these extra simulations, hydrogen was able to penetrate the market, in one case achieving 97% of sales.

In conclusion, there is a pathway that will achieve near zero-GHG emissions in the road freight sector, but the technological makeup of this zero-emissions sector is highly uncertain. Depending on the assumptions I made, forecasts indicate that Canadian goods could be delivered in trucks powered by biodiesel, electricity, or hydrogen. The Canadian government can move forward with strong climate policy to address the road freight sector and, if desired, can reduce industry concerns about uncertainty by purposefully investing in the infrastructure associated with one or more technology options, thus favoring one outcome over another.

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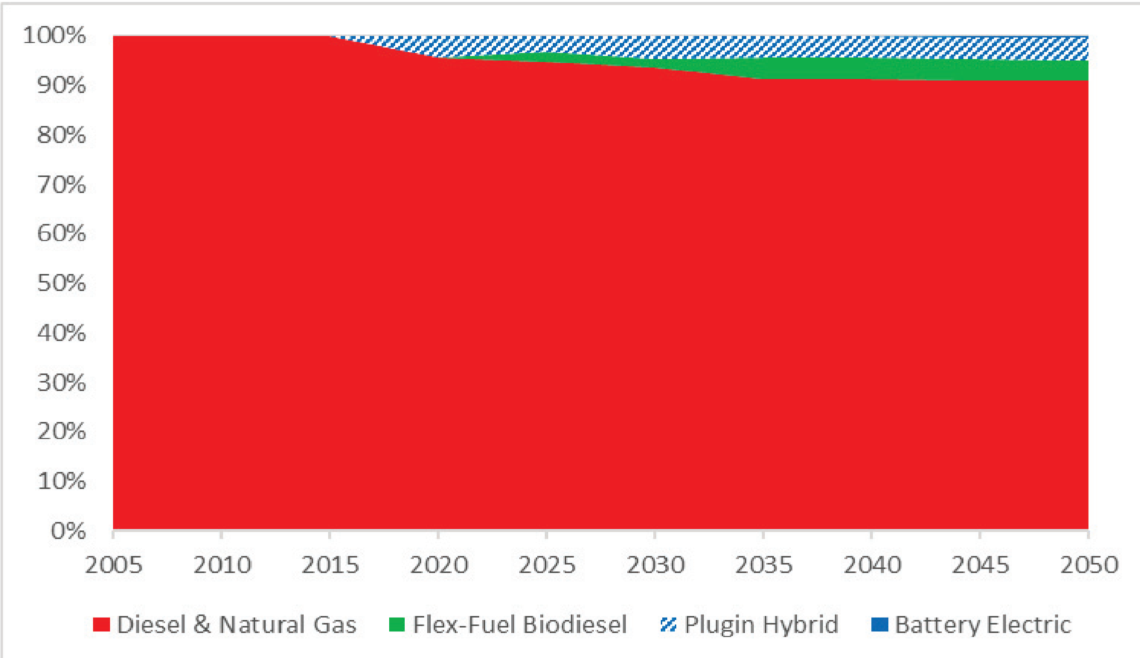
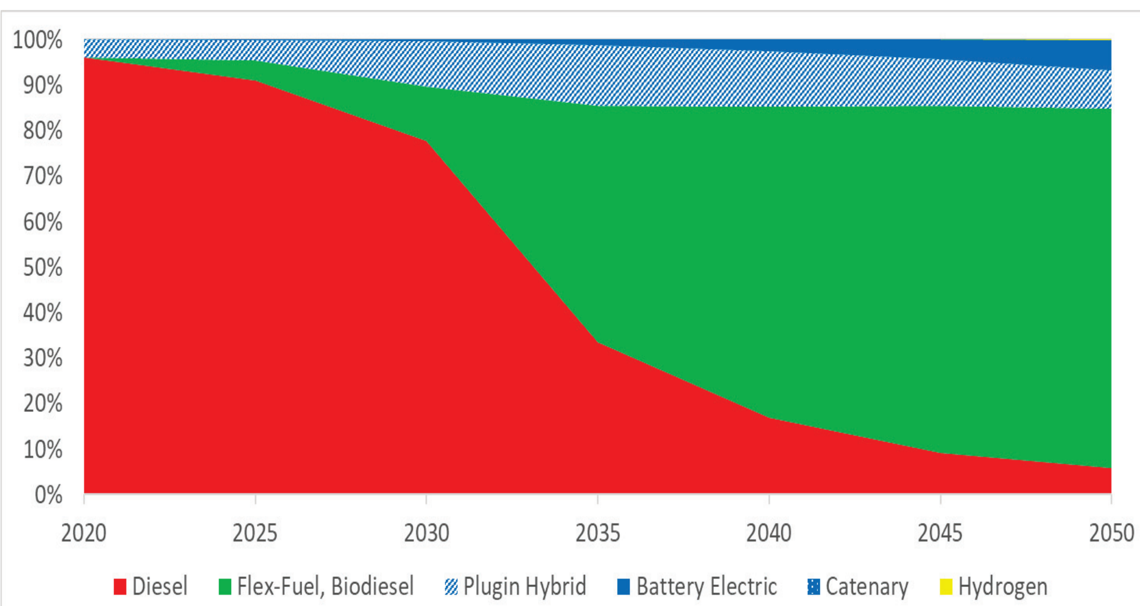
Appendix A. Market Share for All Freight Vehicles in Domestic Action Simulations under Global Inaction

Appendix A1. Market Share for All Freight Vehicles in BAU, Global Inaction

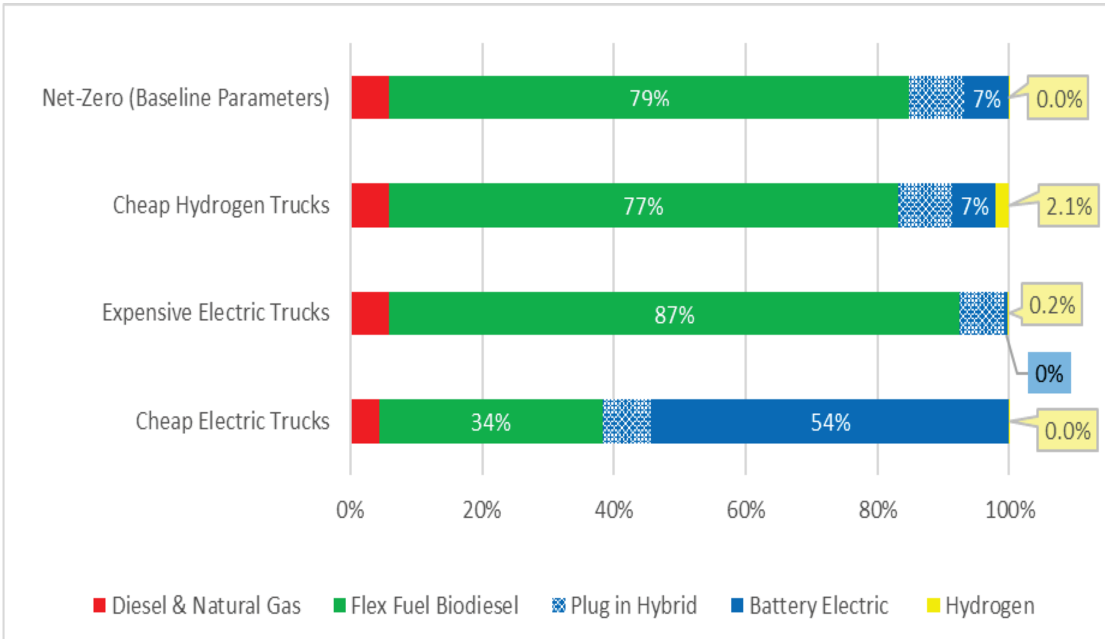


Appendix A2. New Market Share for All Freight Vehicles in Net-Zero, Global Inaction

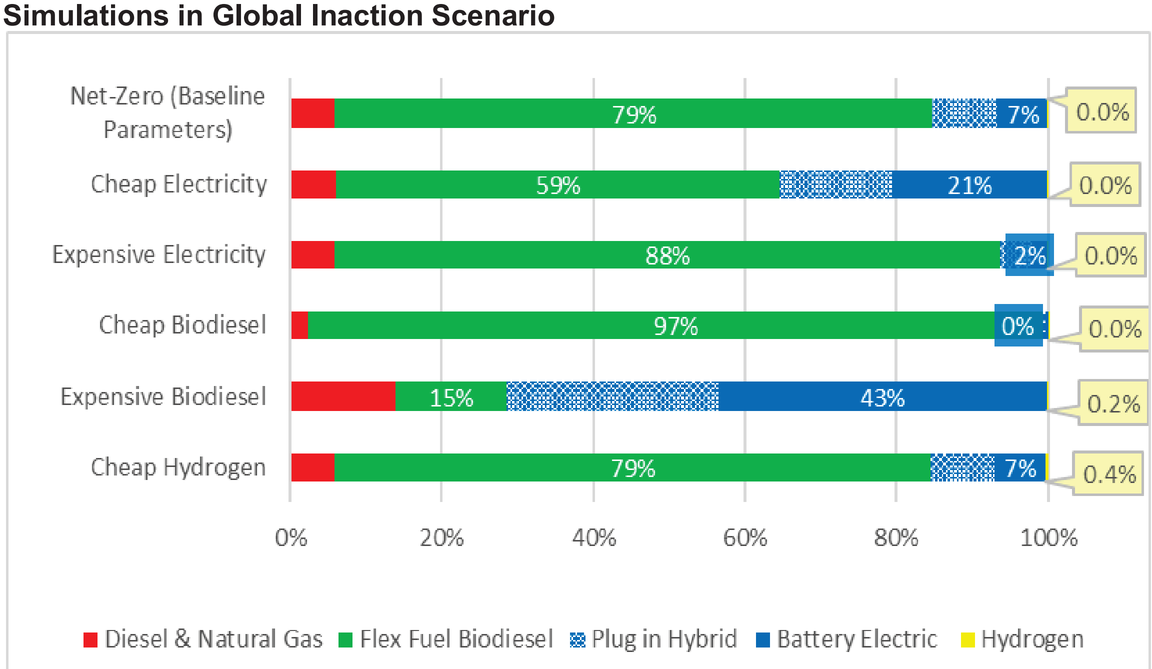


Appendix B. New Market Share for All Vehicles in 2050 under Global Inaction

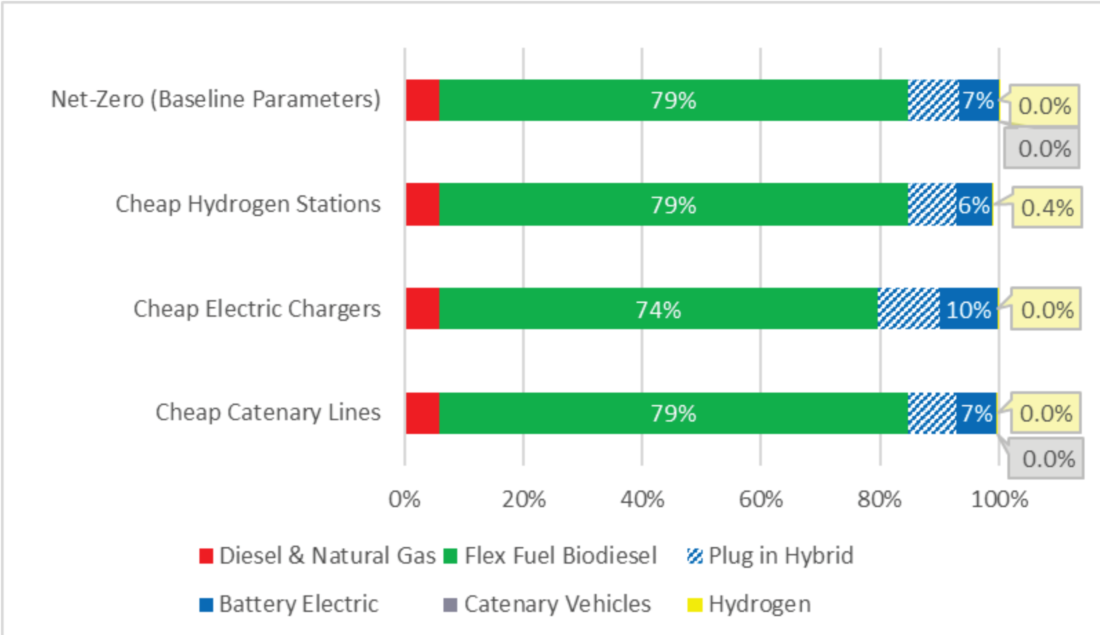
Appendix B1. New Market Share for All Vehicles in 2050 under Vehicle Cost Simulations in Global Inaction Scenario



Appendix B2. New Market Share for All Vehicles in 2050 under Energy Cost Simulations in Global Inaction Scenario

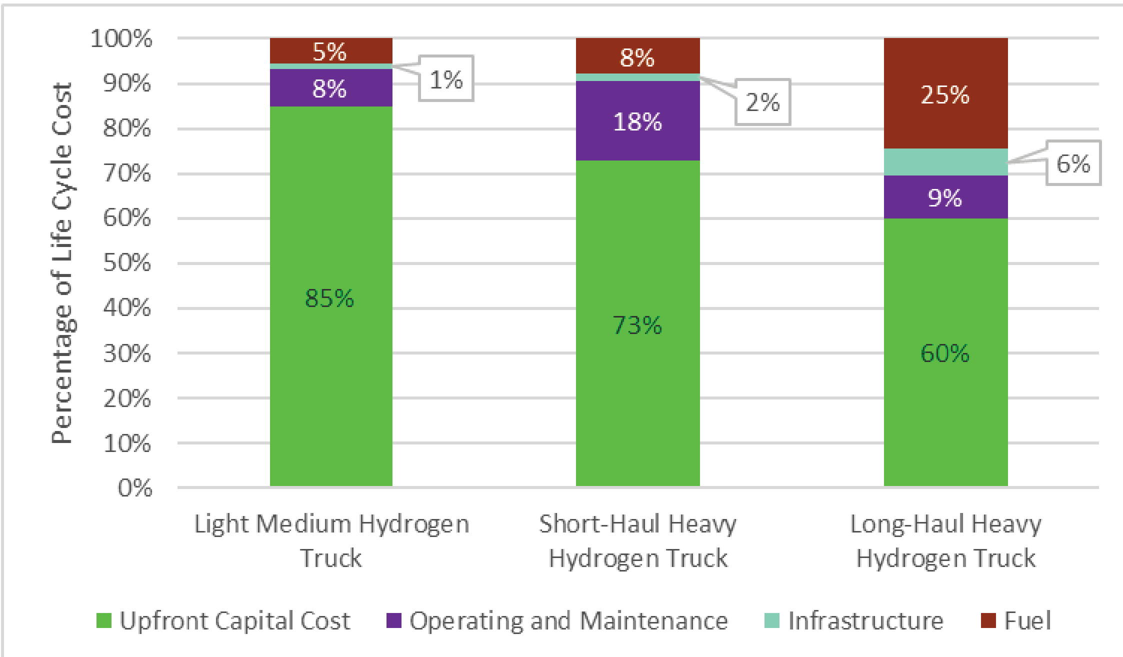


Appendix B3. New Market Share for All Vehicles in 2050 under Infrastructure Cost Simulations in Global Inaction Scenario

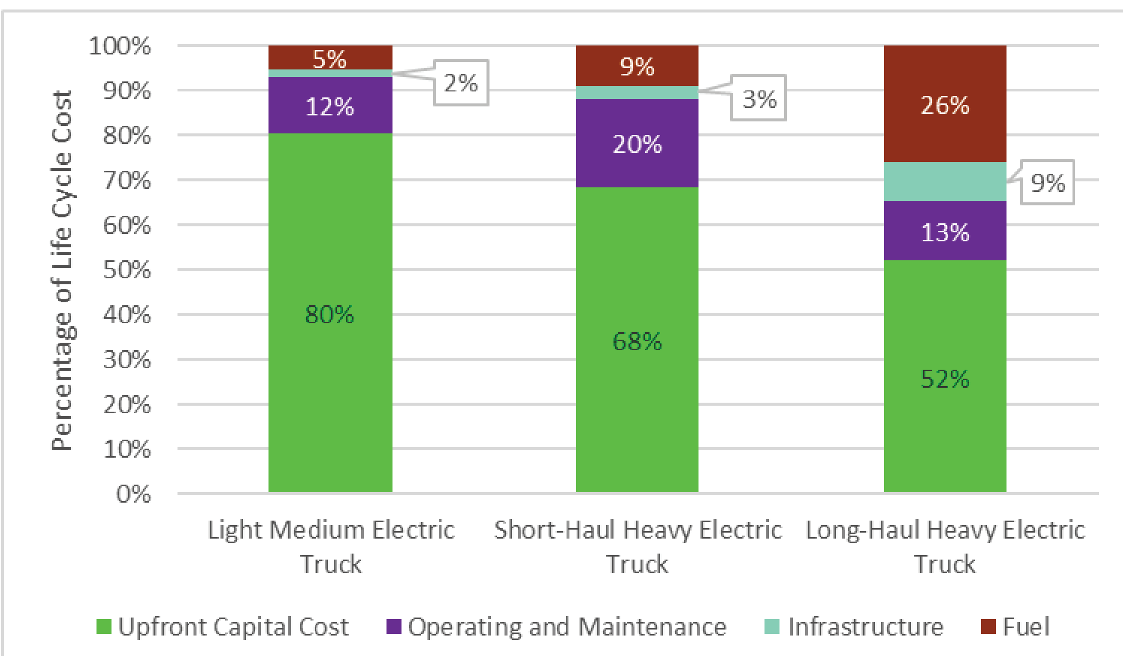


Appendix C. Contributions from Capital, Fuel, Infrastructure, and Maintenance Costs to Truck Life-Cycle Costs in Each Vehicle Mode

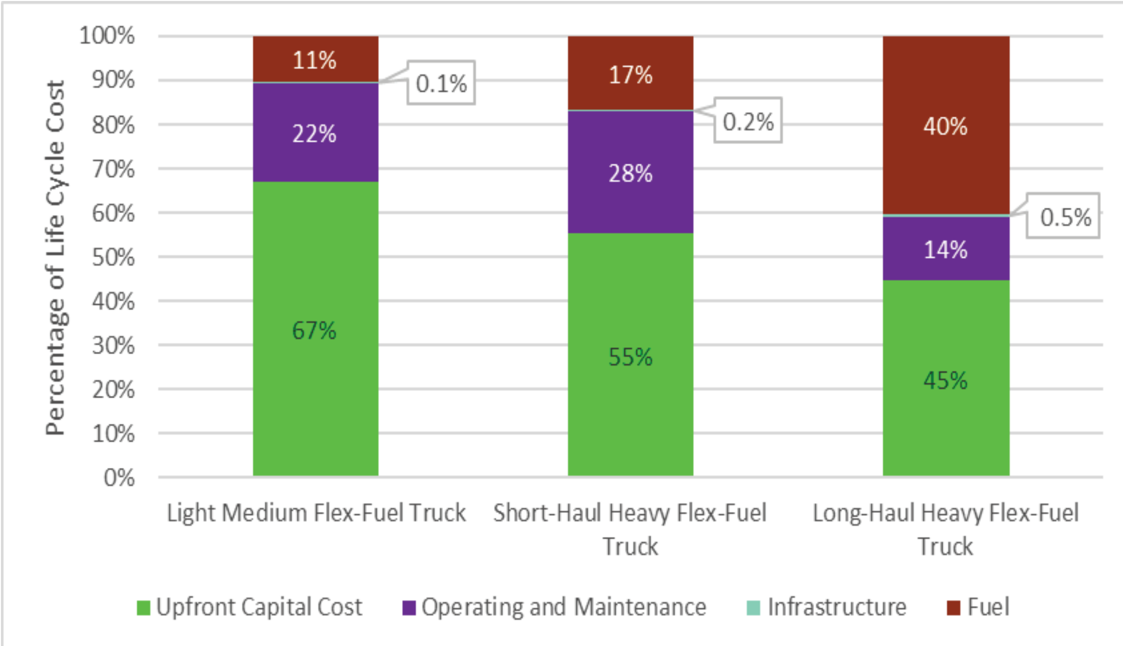
Appendix C1. Life-Cycle Cost Contributions for Hydrogen Trucks in Each Mode



Appendix C2. Life-Cycle Cost Contributions for Electric Trucks in Each Mode

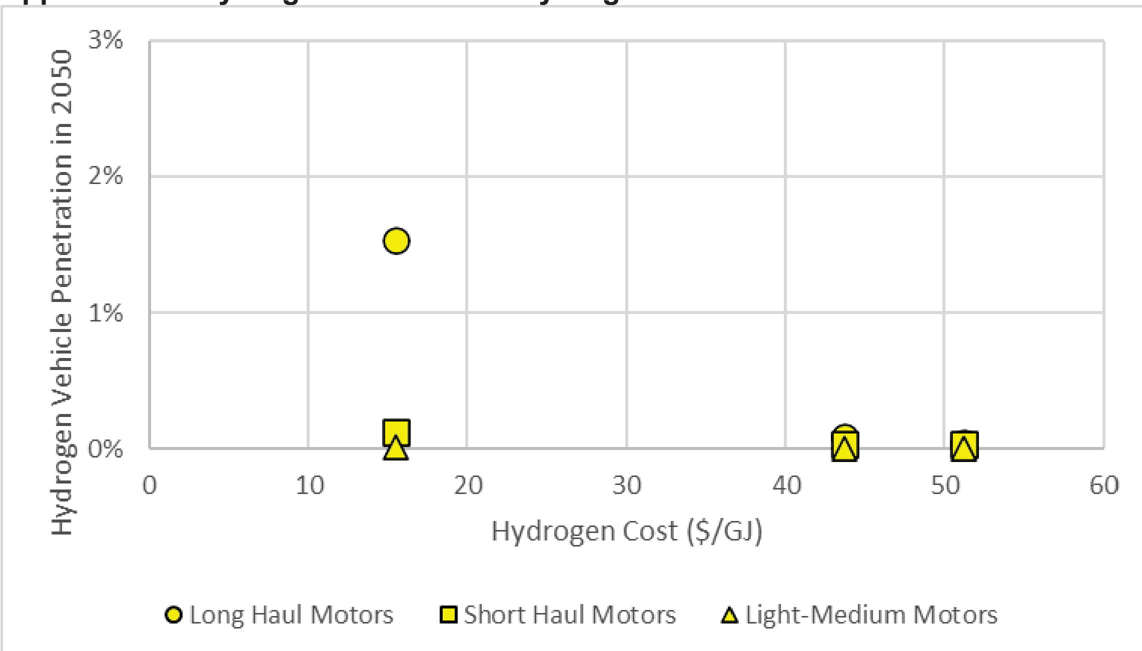


Appendix C3. Life-Cycle Cost Contributions for Flex-Fuel Trucks in Each Mode



Appendix D. Energy Cost Versus Zero-Emission Vehicle Penetration in 2050

Appendix D1. Hydrogen Cost versus Hydrogen Vehicle Penetration in 2050



Appendix D2. Biodiesel Cost versus Flex-Fuel Vehicle Penetration in 2050