Driving Decarbonization:

Pathways and Policies for Canadian Transport

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Executive Summary

As part of the Pan-Canadian Framework on Clean Growth and Climate Change, the Canadian federal government announced plans at the end 2016 to develop a national clean fuel standard (CFS). This report addresses several issues related to applying a CFS to transport.

First, we examine the potential for biofuels to contribute to transport decarbonization. Concerns have been raised that the lifecycle emissions of biofuels may be almost as high as that of oil-derived gasoline and diesel, due to upstream emissions from biofuel production. However, our study suggests that while some biofuel production pathways have high emissions, others have low or even negative emissions. Upstream emissions intensity depends on policy choices. Concerns may also exist about how much biofuels can be produced without having significant impacts on food production and ecosystems. Our analysis of the literature finds that while many uncertainties exist, a substantial quantity of biofuels can likely be produced in Canada without major sustainability repercussions, again depending on policy choices.

Second, we assess the potential for a CFS to be the key policy driving transport decarbonization. Specifically, we examine studies in the literature suggesting that regulations such as a CFS are a costly way to reduce emissions in comparison to carbon pricing. We identify several assumptions that contributed to such findings, including: assuming fixed, high biofuel lifecycle emissions; assuming low social welfare value for personal vehicle mobility; focusing only on policies applied at a weak level of stringency; not testing the most flexible possible regulation variants; and assuming biofuel production has high social and environmental costs.

Third, we conduct a modeling exercise in which we compare a highly flexible CFS with carbon pricing to drive transport decarbonization in Canada. Our results suggest that to achieve the emission reductions required from Canadian transport to meet its 2030 Paris target in an economically efficient manner, a national CFS would require a reduction in average fuel intensity for transport of 15 to 20% by 2030 relative to 2015. This required reduction partially depends on the stringency of policies in other sectors, since growth in freight transport activity depends on the rate of growth in industry and manufacturing. The required intensity reduction for transport would be higher (approximately 20%) if few additional policies are adopted in other sectors, but lower (approximately 15%) if more stringent policies are applied in other sectors. Achieving Canada's 2050 decarbonization goal would require continued reduction of transport emissions intensity, a decline of about 80% relative to 2015.

In our modeling exercise, we employ empirically supported assumptions in comparing flexible regulations to carbon pricing. Our results show similarities in retail fuel prices, vehicle market shares, transport mode choices, and total demand for personal mobility when using either a carbon price or a CFS to achieve the same level of transport emission reductions. This finding suggests that, depending on design, the economic efficiency difference between carbon pricing and a CFS can be small, and that carbon pricing need not play the driving role in decarbonizing the Canadian transport sector.

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Information about the authors and the production of this report

Tiffany Vass has a Masters from the School of Resource and Environmental Management (REM) at Simon Fraser University (SFU). She undertook this project as a research associate in REM's Energy and Materials Research Group (EMRG). Mark Jaccard, a professor at SFU, and a Fellow of the Royal Society of Canada, is the director of EMRG. The authors are solely responsible for this report. While several experts reviewed parts of the report, it has not been subject to a formal external review process.

1. Introduction

In December 2016, the Canadian federal, provincial, and territorial governments released the Pan-Canadian Framework on Clean Growth and Climate Change. The Framework is a culmination of over a year of discussion and negotiation among the governments, and it outlines a wide variety of intended actions targeting different sectors of the economy that together constituent a plan for Canada to mitigate and adapt to climate change. It is intended to put Canada on a path to achieving its international climate change commitments, including its target under the Paris Agreement to reduce emissions by 30% below 2005 levels by 2030 and ultimately much greater reductions by 2050.

The release of the Pan-Canadian Framework is an important step in Canada's efforts to address climate change. However, negotiations are still required to design and implement policies that will succeed in bringing about the coordinated effort outlined in the Framework.

When discussing greenhouse gas emission reductions, it is important to make a distinction between actions and policies. Actions are what people and firms do that result in fewer emissions. Examples include an individual switching from a gasoline to an electric vehicle, an electric utility replacing a coal-fired power plant with wind power, or an oil refinery switching to more energy efficient natural gas boilers. Policies are what governments adopt to spur people and firms to undertake such actions. Examples include an incentive that leads an individual to choose to purchase an electric vehicle over a gasoline vehicle, a regulation requiring an electric utility to close its coal plants and produce more wind power, or a carbon price that spurs an oil refinery to switch to more energy efficient natural gas boilers.

Without effective policy, a climate plan outlining a list of intended outcomes is nothing more than a futile wish list. Adequate policy requires two key characteristics: 1) it must be compulsory, and 2) it must have sufficient stringency to bring about the intended actions. Compulsory policies can take the form of either emissions pricing (which can be implemented as either a carbon tax or cap-and-trade) or regulations (which can be either prescriptive regulations requiring specific actions or flexible regulations that allow for a wider variety of actions to meet the objective). Non-compulsory policies include information campaigns, incentive programs subsidies, and government investment. While these non-compulsory policies may have some role to play in an overall climate plan, they offer no guarantee that people and firms will undertake the actions required to reduce emissions. Compulsory policies must be adopted at sufficient stringencies – that is, the emissions price must rise to a high enough level or the regulation must have stringent enough requirements – to drive people and firms to take actions that together will meet the intended emissions reduction objective.

The policy development work that occurs over the coming months and years will be crucial to determining the success of the Pan-Canadian Framework. Some policies will be relatively straightforward to develop, while others will require numerous design decisions and attention to intricate policy details. One policy that has the potential to achieve substantial emission reductions and will require attention to policy details is the intention to develop a clean fuel standard (CFS).[1]

The federal government has begun consulting with stakeholders to develop the CFS. The target timeline would see the final regulations published in the *Canada Gazette* in 2019. The government has stated that the objective of the CFS is to achieve 30 Mt of emission reductions in addition to what will be achieved by current measures. While clean fuel standards have been used in other jurisdictions only for transportation fuels, as of mid-2017, the government intends for the CFS to cover fuels used in not only transport but also industry and buildings.

Given the CFS's potential importance, we have produced this report with a focus on issues of relevance to its design. We have chosen to focus on its application in transport since this is the sector for which this policy type is normally applied. Our intent is to explore the potential actions that can contribute to decarbonizing transport and the potential contribution of a CFS in spurring those actions.

A variety of actions can contribute to reducing emissions in transport. These actions fall within several broader categories:

1) **Fuel switching:** switching the fuels used by vehicles from high carbon fuels, such as gasoline and diesel, to lower carbon fuels, such as biofuels, electricity and hydrogen.
2) **Energy Efficiency improvements:** switching to vehicles that use less fuel per distance travelled.
3) **Mode switching:** switching to different modes of transportation; in personal transport, switching from single occupancy vehicles to carpooling, transit, cycling and walking; in heavy freight, switching from trucks to rail.
4) **Demand reduction:** reducing total distance traveled; in personal transport, this could involve telecommuting, living closer to work, or opting to spend vacation time closer to home; in freight transport, this could occur if fewer, smaller and lighter goods are being produced and consumed, thus reducing transport energy needs.

While a CFS is focused on fuel switching, it will also impact fuel prices, which in turn leads to actions in other categories. Key fuels that have potential to contribute to transportation decarbonization include biofuels and electricity, although hydrogen should not be ruled out.

We spend part of this report especially assessing the potential for biofuels to contribute to decarbonizing transport. We do this for several reasons. First, concerns have been raised that emissions from producing biofuels could make biofuels hardly better than fossil fuels in terms of lifecycle emissions. Thus, we see a need to probe the issue of upstream emissions from biofuel production. Meanwhile, electricity production is already near zero-emission in many provinces

[1] Often in this report, we include electricity in our definition of fuels. This break with a long-standing convention results from California's inclusion of potential gasoline and diesel substitutes, such as electricity, hydrogen, and biofuels, in its definition of fuels when creating its clean fuel regulation in 2007. Thus, when talking about flexible regulations designed to influence the choice of energy for transport, we and other analysts are also referring to electricity and other forms of energy when using the word fuels.

in Canada, and policies have been adopted to substantially decarbonize electricity production by 2030 in the remaining provinces. Hence, upstream emissions for electric vehicles is rapidly becoming less of a concern. Second, concerns have been raised that the potential to sustainability produce biofuels may be limited due impacts on ecosystems and food production. Thus, we address the issue of how much biofuels could likely be produced sustainably in Canada.

We also address concerns about using a flexible regulation such as CFS as a key policy for decarbonizing transport. In particular, concerns have been raised that CFSs and other regulations are an economically inefficient policy choice in comparison to carbon pricing. An economically efficient policy achieves a given amount of emissions reductions at the lowest possible cost. Economic efficiency tends to be maximized when there is a uniform pollution price signal throughout the economy. That uniform price signal ensures that firms and households, if they are trying to minimize costs, will only reduce those emissions for which the cost of doing so is cheaper than paying an emissions price or a regulatory fee[2]. Like most economists, we accept the empirical research showing that carbon pricing, if designed properly, can be more economically efficient than regulations. However, designing regulations to mimic many of the flexibility effects of carbon pricing may reduce the economic efficiency loss. Additionally, some types of regulations may have the advantage of being more politically acceptable than carbon pricing at stringencies that are high enough to achieve ambitious yet economically justifiable emission reduction targets[3]. These attributes may explain why jurisdictions that are implementing carbon pricing, such as California, British Columbia, Ontario, and the Canadian government, are simultaneously implementing CFSs in transport sectors.

In this report, we explore the implementation of a CFS that the Canadian government would apply across the country. We hope to contribute to the policy design discussion by focusing on the application of this CFS to the transport sector. But the general lessons from our analysis can be relevant to the multi-sector application that the federal government is considering. Specifically, we combine literature evidence and our own energy-economy simulation modeling exercise to address the following objectives:

1. Assessing the potential contribution of various actions to rapidly reducing the use of fossil fuels in transport.
2. Exploring how a CFS could be the driving policy for rapidly reducing emissions in transport.
3. Assessing the likely economic efficiency losses from reliance on a CFS instead of pure emissions pricing, using market share outcomes and fuel prices as a proxy.

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[2] Economists refer to this as the equi-marginal principle, a key concept when it comes to the pursuit of economic efficiency with environmental policy design.

[3] For more detailed discussion of the potential political acceptability advantages of flexible regulations over carbon pricing see Jaccard, M., Hein, M. & Vass, T. (2016). Is win-win possible? Can Canada's government achieve its Paris commitment . . . and get re-elected?. Simon Fraser University, Energy & Materials Research Group Research Report. Available at http://rem-main.rem.sfu.ca/papers/jaccard/Jaccard-Hein-Vass%20CdnClimatePol%20EMRG-REM-SFU%20Sep%2020%202016.pdf

The remaining sections of this report comprise the following: Section 2 addresses concerns about the potential for biofuels to contribute to decarbonizing transport; Section 3 discusses key literature on using regulations to decarbonize transport; Section 4 explains the scenarios that we model; Section 5 outlines our modeling method; Section 6 presents and discusses our modeling results; and Section 7 presents our conclusions and the study's limitations.

2. The Potential Role of Biofuels in Decarbonizing Transport

Biofuels are a commercially available alternative to gasoline and diesel use in transport. Canada currently has approximately 13 ethanol producers with a combined annual capacity of 1,957 million litres per year and 9 biodiesel producers with a combined capacity of 657 million litres per year[4]. Ethanol is currently blended into gasoline to make up approximately 6% of the blend, and biodiesel blended into diesel to make up approximately 2% of the blend[5]. Brazil, in contrast, has achieved higher rates of biofuel production and consumption, with ethanol accounting for 60% of the blend in gasoline-ethanol fuel[6]. Ethanol-85 flex fuel vehicles are commercially available that can take up to 85% ethanol blends, and trucks are commercially available that can run on 100% biodiesel[7].

Fossil-fuel derived gasoline and diesel are usually the cheaper option for vehicle transport when climate impacts are ignored, which is why low-emission alternatives like biofuels, electricity and hydrogen need the support of climate policy. Undoubtedly, technological developments of certain biofuel pathways may reduce biofuel costs as well as impacts on food prices and biodiversity (such as second generation biofuels produced from non-food feedstocks and third generation biofuels produced from algae). However, given that many biofuel production pathways are already available, this technological development is not a pre-requisite for biofuels to contribute to replacing gasoline and diesel. Biofuels have the potential to play a particularly important role in heavy freight trucking, marine freight, and aviation, where other options such as electricity and hydrogen face higher barriers and have been slower to develop.

But although biofuels are a commercially available alternative to fossil fuel use in transport, concerns have been raised about the potential for biofuel lifecycle emissions to achieve

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[4] Renewable Industries Canada. (2015). Canadian ethanol and biodiesel facilities. Retrieved from: http://ricanada.org/wp-content/uploads/2015/03/Canadian-Ethanol-and-Biodiesel-Facilities-Producer-Tables-for-Website.pdf

[5] USDA. (2016). Canada: Biofuels Annual 2016. Global Agricultural Information Network. https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Ottawa_Canada_8-9-2016.pdf

[6] USDA. (2016). Brazil: Biofuels Annual 2016. Global Agricultural Information Network. https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Sao%20Paulo%20ATO_Brazil_8-12-2016.pdf

[7] USDA. (2017). Flex fuel vehicles. https://www.afdc.energy.gov/vehicles/flexible_fuel.html; Scania. (2014). Scania adds 13-litre biodiesel engines to its Euro 6 range. https://www.scania.com/group/en/scania-adds-13-litre-biodiesel-engines-to-its-euro-6-range/

substantial reductions relative to fossil fuels and for biofuels to be produced sustainably[8]. This section reviews each of these concerns in turn.

2.1. Biofuel Lifecycle Emissions

When comparing emissions of different transport fuels, it is useful to consider their lifecycle emissions. These extend from the upstream emissions from producing the biomass and then the fuel itself to the combustion emissions when the fuel is burned to power the vehicle.

For biofuels, the carbon dioxide released during fuel combustion is considered carbon neutral, since the carbon was recently absorbed from the atmosphere by growing plants. Returning it to the atmosphere does not result in a net increase in the amount of carbon in the atmosphere. However, emissions from fossil fuels may be released during the upstream stages of producing biomass and converting this into biofuels. Producing biofuels requires producing and harvesting biomass feedstocks, processing these into biofuels, and transporting feedstocks and the final biofuel products.

While in some instance the emissions from producing biofuels may make biofuels hardly better, or in some cases worse, than fossil fuels in terms of net emissions, biofuels can also be produced with low or in some cases even negative lifecycle emissions. (Negative emissions can occur when co-products, land use change, or reduction in emissions from waste result in a net removal of carbon from the atmosphere as compared to if the biofuels hadn't been produced.) Thus, rather than using diesel to fuel the tractors and trucks that harvest feedstocks, biodiesel can be used. Rather than using coal or natural gas to fuel boilers that convert feedstocks to biofuels, biomass in solid or gaseous form (biomethane) or zero-emission electricity can be used.

The lifecycle emissions of biofuels that are currently being produced vary widely. British Columbia and California are two jurisdictions that have been measuring lifecycle emissions of biofuels for their flexible fuel regulations (called low carbon fuel standards), using the GHGenius and GREET lifecycle models, respectively. The lifecycle emission measurements include emissions from fossil fuels during biofuel production, land use change emissions (direct land use emissions in British Columbia; direct and indirect land use emissions in California), and emissions displaced due to production of co-products along with biofuels, such as animal feed or electricity through co-generation. The measured carbon intensities are evidence that while some biofuel production methods do have high net emissions, biofuels can in fact be produced with very low emissions.

For ethanol pathways, approved lifecycle carbon emission intensities under the British Columbia Renewable and Low Carbon Fuel Requirements Regulation (LCFS) range from -54.80 to 81.64 gCO_2e/MJ[9] and under the California Low Carbon Fuel Standard Regulation range from 7.18 to

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[8] As one example, see Searchinger, T. & Heimlich, R. (2015). Avoiding bioenergy competition for food crops and land. Creating a sustainable food future, Installment nine. World Resource Institute. Available at: http://www.wri.org/publication/avoiding-bioenergy-competition-food-crops-and-land

[9] BC Government. (2016). Transportation fuel lifecycle assessment. Retrieved from http://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/renewable-low-carbon-fuels/fuel-lifecycle-assessment

88.90 g/MJ[10]. For biodiesel pathways, approved carbon intensities under British Columbia's LCFS range from -15.74 to 98.96 g/MJ and under California's LCFS range from 8.63 to 61.94 g/MJ. This compares to lifecycle emissions of 87.29 and 98.47 g/MJ for gasoline and 93.55 and 102.01 g/MJ for diesel, as measured by British Columbia and California, respectively. The exact carbon intensity value assigned to a biofuel pathway can vary depending on assumptions, including the method of accounting for land-use change and for co-products. Nonetheless, the fact that both British Columbia and California have assigned either negative or near-zero carbon intensity values to some biofuel pathways indicates that methods already exist to produce biofuels with very low emissions.

One illustrative example of low carbon biofuel production is the ethanol produced by Greenfield Global (formerly Greenfield Speciality Alcohols Inc.) in Chatham, Ontario. The ethanol plant, which uses corn as a feedstock input, reduces its carbon footprint by pumping CO_2 and waste heat for use in a neighbouring greenhouse[11]. Another example is the ethanol produced by the Enerkem Alberta Biofuels facility in Edmonton, Alberta. The facility uses municipal solid waste to produce ethanol, methanol, and other bio-based chemicals[12]. Enerkem's biofuel pathway was assigned a carbon intensity of -54.80 g/MJ under the BC low carbon fuel standard.

Land use change is one aspect of measuring biofuel lifecycle emissions that involves substantial uncertainties and complexities. Land use emissions can result from both direct and indirect land use change. Direct emissions include release of greenhouse gases and loss of carbon sinks from vegetation and soils due to actions such as clearing forested land, bringing new land into cultivation, and changing the amount of nitrogen fertilizers applied to croplands. Some aspects of direct land use emissions, such as the dynamics of soil carbon storage, are rather complex, and scientific understanding continues to evolve[13]. Indirect emissions occur when energy crop production displaces crop or fibre production in one location, leading to changes in land use and hence land use emissions in another location to meet demand for crops and fibre. Indirect emissions are particularly complicated to evaluate, since it is difficult to determine direct cause and effect relationships between biofuel production in one area and land use change in another. Given the complexities and uncertainties of measuring land use emissions, evaluations range from those finding that land use emissions are inconsequential or even negative, to those finding that land use emissions could cause the lifecycle emissions of biofuels, for a period of time, to be higher than that of fossil fuels[14].

While it is true that land use emissions from biofuels could lead to a small net increase in atmospheric greenhouse gas concentrations over the short-term, it is important to remember that stabilizing atmospheric concentrations of greenhouse gases is a long-term objective. When

[10] California Air Resources Board. (2016). LCFS Pathway Certified Carbon Intensities. Retrieved from https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm
[11] Pin, L. (Sept. 26, 2016). 'Truly Green, GreenField invest $8 million into eco-friendly agriculture innovation'. *Chatham Daily News*. Retrieved from http://www.chathamdailynews.ca/2016/09/26/truly-green-greenfield-invest-8-million-into-eco-friendly-agriculture-innovation
[12] Enerkem. (2017). Enerkem Alberta Biofuels. http://enerkem.com/facilities/enerkem-alberta-biofuels/
[13] GEA. (2012). Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.
[14] IEA. (2011). Technology roadmap: biofuels for transport. International Energy Agency. Paris, France.

discussing land use emissions, studies sometimes refer to 'carbon payback times' – the amount of time it takes for biofuels to lead to net greenhouse gas emissions reductions when accounting for changing land use emissions. Payback times when converting land for biofuel production can be instantaneous for degraded or already cultivated land, less than a decade for lands with low carbon stocks such as grasslands, and several decades if from cutting forests that would otherwise never have been harvested[15]. Destroying peat soils, which may occur when creating palm oil plantations in tropical regions, may have much longer carbon debts[16].

When looking at net emissions over several decades, the possibility of a small amount of direct land use emissions in the short-term has the potential to be greatly outweighed by the benefit of reduced emissions from fossil fuels over the next decades and centuries. Carbon stored in plants was assimilated relatively recently and is not permanently stored since natural events such as forest fires could release it back into the atmosphere. On the other hand, carbon in fossil fuels has been in storage for millions of years and would remain there permanently if humans did not extract and burn it. Additionally, if the consumption of bioenergy releases carbon from plants into the atmosphere, that carbon can generally be re-assimilated within reasonable timescales. For example, even using a moderate amount of high-carbon-storage trees for bioenergy should not result in a large, permanent flux of carbon into the atmosphere, since trees can be re-planted on that land and over time re-absorb the released carbon. Even if some forested land is permanently converted to cropland for biofuel production, the land could continue to produce biofuels and thus prevent decades and even centuries of carbon release from fossil fuel extraction and combustion.

Nevertheless, efforts to minimize the amount of land use change emissions resulting from biofuel production should be undertaken where possible, since it is preferable to maintain more rather than less carbon storage in plants and soils. Policy and planning can and should be used to minimize the potential for substantial land use change emissions. Various methods can be used, including using wastes and residues as feedstock when possible, increasing yields on land that is already in production, producing energy crops on unproductive and low-carbon soils, using feedstocks efficiently in the fuel production process, and co-producing energy and food crops[17]. Methods such as these can help reduce competition with other land uses, such as food production, and thus minimize the need to bring substantial amounts of new land into production and minimize the potential for direct and indirect land use emissions. Additionally, for those feedstocks that do have very long carbon debts, in particular palm oil feedstocks that cause destruction of high carbon peat soils, it may be useful to adopt controls to limit their use in biofuels.

In sum, while some uncertainties regarding land use emissions remain, it appears that biofuels can be produced in ways that lead to either high or low lifecycle emissions. And policy can be

[15] GEA. (2012). Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.
[16] Union of Concerned Scientists. (2013). Palm oil and global warming. Fact Sheet. Retrieved from http://www.ucsusa.org/sites/default/files/legacy/assets/documents/global_warming/palm-oil-and-global-warming.pdf
[17] IEA. (2011). Technology roadmap: biofuels for transport. International Energy Agency. Paris, France.

designed to incentivize shifting towards increasingly lower-emission methods so that biofuels might achieve substantial emission reductions relative to fossil fuels.

2.2. Sustainable Biofuel Potential

The theoretical potential to produce biofuels is vast – it has been estimated that annual global terrestrial above-ground net primary biomass production is approximately 1,260 EJ/year, which is about 2.5 times the current 500 EJ/year total global energy supply[18]. Fully realizing this theoretical energy potential would mean that no biomass would be available to meet human food and fibre needs, and the resulting mass clearing of vegetation would have severely harmful impacts on natural ecosystems and lead to an initial increase in atmospheric concentrations of greenhouse gases due to reductions of carbon sinks. This clearly would not be sustainable. Fortunately, no one is suggesting that all global net primary biomass production be turned into bioenergy. Instead, a pragmatic approach would see bioenergy as one of a variety of energy sources potentially contributing to a low carbon energy system.

Various studies have sought to estimate what amount of bioenergy could be sustainability produced. While the precise definitions of sustainable production vary, criteria often involve ensuring that human food and fibre needs are met prior to producing bioenergy and that substantial harm to ecosystems and biodiversity is avoided. Consideration is also often given to the impact of land use change on carbon stocks and the net greenhouse gas balance.

Considerable uncertainty exists surrounding estimates of sustainable bioenergy potential. The area of land required to meet global demand for food rests on a number of uncertain factors, including the amount and composition of food demand (itself a function of factors such as population growth, income growth, and change in the relative demand for plant versus animal based products), agricultural yields, and the efficiencies of feeding livestock[19]. The influence of climate change and water scarcity on crop yields is also uncertain, as are future demands for fibre use and the level of priority placed on biodiversity conservation. Finally, increased demand for biofuel would change land, food and fibre prices, which in turn would trigger innovations and land-use shifts that might significantly increase global bioproductivity. Thus, estimates of sustainable biofuel potential vary widely and can change in response to market developments, such as an increased demand for biofuels. Nonetheless, looking at leading studies can provide an order of magnitude approximation of what minimum amount of bioenergy could be available.

The International Energy Agency's Biofuels for Transport Technology Roadmap estimates that biofuels could sustainably provide 27% of global demand for transport fuels by 2050[20]. This would amount to 65 EJ of biomass to produce transport biofuels and would be in addition to

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[18] Chum, H., A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, B. Gabrielle, A. Goss Eng, W. Lucht, M. Mapako, O. Masera Cerutti, T. McIntyre, T. Minowa, K. Pingoud. (2011) Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[19] GEA. (2012). Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.
[20] IEA. (2011). Technology roadmap: biofuels for transport. International Energy Agency. Paris, France.

another 80 EJ of biomass for heat and power. The Roadmap notes that a 2008 review by Dornburg et al. estimated the sustainable bioenergy potential to reach 475 EJ by 2050, which is three times the 145 EJ total bioenergy required by 2050 in the IEA's scenario. Producing the 65 EJ of biomass for transportation biofuels would involve a combination wastes and residues, increased agricultural productivity on existing agricultural land, and some expansion of energy crops on to new land. The new land would include cropland, pastureland, and some currently unused or minimally used land, and would increase the percent of total arable land used for biofuel production from about 2% today to about 6% in 2050.

The Global Energy Assessment (GEA) provided estimates of sustainable bioenergy potential in 2050 for the world and by region, which were developed from a comprehensive review of leading academic studies on the topic. We present data for Canada, the US, and the world in Table 1[21]. If the entire global sustainable biomass supply was converted to transport fuels (i.e. none was used for heat and electricity), it would amount to approximately 65 to 85% of the 95 EJ of total global demand for transport fuels in 2008. Along similar lines, the 1.7 to 2.2 EJ of sustainable transport fuel production potential for Canada would amount to approximately 64 to 82% of Canada's 2.68 EJ of demand for fuels in the transport sector in 2014[22]. Note that total consumption of petroleum based fuels in all sectors in Canada in 2014 was approximately 3.7 EJ. In a global market, Canada's biofuel production would not necessarily all be consumed domestically, nor would Canada's biofuel consumption necessarily all be produced domestically; however, the Canada-specific estimate does provide a sense of national production potential.

Table 1: Global Energy Assessment (2012) Estimate of Sustainable Biomass Feedstock Supply in 2050 and the Resulting Supply of Transportation Fuels

	2050 potential sustainable biomass supply (EJ/yr, hhv)						**Conversion to transport fuels (EJ/yr LHV)**	
	Crop residues	*Animal waste*	*MSW*	*Forest residues*	*Energy crops*	***Total***	*Low*	*High*
Canada	0.6	0.47	0.12	2	2.45	**5.6**	1.7	2.2
US	3.28	3.03	1.33	7	11.09	**25.7**	7.8	10
World	49	39	11	27	88	**215**	63	81

Note: The supply of transportation fuels assumes that all feedstock is used for transportation biofuels, and none for electricity and heat production. MSW = municipal solid waste. LHV = lower heating value.

The Global Energy Assessment discusses the uncertainty surrounding these estimates. In particular, the GEA authors consider estimates for energy crop production highly uncertain. Their estimates for energy crop potential were derived from the estimates contained in three global studies, considered to be comprehensive in their consideration of sustainability criteria. Each of those studies contained a range of estimates. For Canada, the estimates for sustainable

[21] GEA. (2012). Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.
[22] Natural Resources Canada. (2017). Comprehensive Energy Use Database. Retrieved from http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm

energy crop potential ranged from 0 to 4 EJ, and for the world the range was 28 to 146 EJ. Thus, the actual sustainable biomass potential could be considerably higher or lower than the central estimates, and has an element of subjectivity based on the strictness of the sustainability criteria that was applied.

While global studies are relevant because of the integrated nature of the global energy system, country-specific studies help assess the bioenergy potential of individual countries with finer detail. A study by Liu et al. looked at the potential to grow dedicated energy crops on marginal land in Canada (land with low productivity that would be unprofitable for growing food crops)[23]. They estimated that approximately 9.5 million hectares (1% of Canada's total land area) of marginal land could be available for growing bioenergy crops, which could produce 380 million tons of hybrid poplar. This biomass could produce approximately 2.2 to 2.9 EJ of biofuels, or between 84 and 108% of Canada's total transport fuel consumption in 2014[24]. Note that this study did not discuss applying sustainability criteria, which may explain why this estimate exceeds that of the Global Energy Assessment[25].

A recent study by the US Department of Energy examined the potential to produce biomass feedstock in the US, one of Canada' main trading partners[26]. The comprehensive study used detailed county-level spatial and economic data and modeling of factors ranging from soil quality to forestry production. It assumed that biomass would only be used for bioenergy after the demand for food, feed, fibre and timber had been met. The results found that 1 billion tons of biomass could be produced annually, with minimal to negligible environmental effects in terms of soil organic carbon, greenhouse gas emissions, water quality and quantity, air emissions, and biodiversity. The 1 billion tons could translate to approximately 7.5 EJ of transport fuels, or about 30% of current US consumption of petroleum-based fuels[27]. This is close to the lower range estimates for transport fuel production from the Global Energy Assessment.

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[23] Liu, T., Ma, Z., McConkey, B., Kulshreshtha, S., Huffman, T., Green, M., Liu, J., Du, Y., & Shang, J. (2012). Bioenergy Production Potential on Marginal Land in Canada. In Proceedings of the 2012 First International Conference on Agro-Geoinformatics (Agro-Geoinformatics), Shanghai, China, 2–4 August 2012; pp. 1–6

[24] Assuming that woody biomass produces between 5.9 and 7.6 GJ of fuel/ton (lower heating value), based on estimates from GEA (2012). Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

[25] Another study of note is a review article looking at various estimates of biomass availability in Canada from different biomass sources: Gronowska, M., Joshi, S. and MacLean, H. (2009). US and Canadian biomass. *BioResources*, 4(1): 341-369. The variability in estimates within the literature is evident in Appendix 2 of that study.

[26] U.S. Department of Energy. (2016). 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p. doi: 10.2172/1271651. http://energy.gov/eere/bioenergy/2016-billion-ton-report.

[27] Assuming an average tonne of biomass produces 7.5 GJ of fuel, a middle ground approximation based on estimates for various biomass sources in the GEA (2012). Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria. Note that US petroleum consumption for energy uses was approximately 26.9 EJ in 2014, IEA. (2017). United States: Balances for 2014. IEA Statistics. Retrieved from: http://www.iea.org/statistics/statisticssearch/report/?country=USA&product=balances&year=2014.

One of the most controversial aspects is the perceived potential for biofuel production to compete with food production and increase food prices, leading to hardship particularly in developing countries. As mentioned above, many studies examining sustainable biofuel potential assume that demand for food is met prior to producing biofuels, a concept sometimes referred to as the 'food first' principle. Even substantial growth in food demand does not likely preclude the possibility to also produce bioenergy. The United Nations Food and Agriculture Organization (FAO) estimates that global food demand will increase by approximately 70% by 2050, as the global population rises to over 9 billion[28]. FAO estimates that higher yields and crop intensity could satisfy 90% of the additional demand, with the remaining demand met by an expansion of 70 million hectares of arable land (less than 0.5% of global land area). Much of the expansion of arable land is expected to take place in developing countries, while use of arable land is projected to decrease by 50 million hectares in developed countries. Thus, given the projected increase in agricultural yields and shifting land use particularly in developed countries, using some amount of land for producing bioenergy crops need not necessarily be in direct competition with increased food production.

Even in the absence of supply shortages for food commodities, the dynamics of markets are such that there is potential for some degree of increase in food commodity prices as a result of increased demand for bioenergy feedstocks. The IPCC reviewed various studies that sought to estimate the role of biofuel production in food price surges in the mid-2000s[29]. While the studies generally were in agreement that biofuel production likely had some effect on food prices, estimates differed in terms of the size of the effect. Many other factors likely played a role, including a weak US dollar, increased costs of energy and agricultural production, commodity speculation, and a period of unfavourable weather conditions.

Given that food commodity prices regularly fluctuate due to a variety of complex factors, ensuring food security for the world's poor will require adequate policy measures and planning[30]. While increased food prices can hurt food purchasers, they can also provide added income for food producers in developing countries. Furthermore, increased use of bioenergy can provide increased income opportunities and enhance energy security in the developing world. Thus, taking a holistic, integrated approach to policy and planning for food and bioenergy production has the potential to lead to synergies among food security, energy security and poverty alleviation. Furthermore, it is of note that over the long term, biofuel production is projected to move increasingly away from conventional biofuels that make use of oil and starch-based feedstocks (which could also be used as food) and increasingly towards advanced biofuels that

[28] Cited in IEA. (2011). Technology roadmap: biofuels for transport. International Energy Agency. Paris, France.
[29] Chum, H., A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, B. Gabrielle, A. Goss Eng, W. Lucht, M. Mapako, O. Masera Cerutti, T. McIntyre, T. Minowa, K. Pingoud. (2011) Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[30] GEA. (2012). Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

make use of wastes, residues, and dedicated energy crops grown on less productive lands[31]. This would reduce the potential for competition with food.

The issue of the likely interaction between biofuels and food markets is indeed complex, and a full in-depth analysis is beyond the scope of this study. Nonetheless, our brief overview shows why a balanced policy approach that aims for both food security and a modest amount of biofuel production is likely more appropriate than a view that sees food and fuel production as diametrically opposed objectives.

In conclusion, despite various uncertainties, trade-offs, and constraints, there may be significant potential for sustainable bioenergy production. Adequate policy and land use planning can help to promote sustainable production, reduce the potential for negative impacts, and minimize competition between bioenergy, food and fibre markets. Policies could include sustainable land-use management and certification schemes that help ensure biodiversity protection and policies that support improved efficiency of conventional biofuel production and commercialization of advanced biofuel production[32]. Investment in increasing agricultural yields will also likely be important to achieve higher sustainable bioenergy potentials, and this response is likely to be triggered by modest increases in the prices of land, food and fibre.

3. The Potential Role of Regulations in Decarbonizing Transport

Various studies have examined the use of regulations to reduce emissions in transport. Several have specifically compared the use of regulations with the use of carbon pricing, concluding that regulations are substantially costlier than carbon pricing. In this section, we discuss some of these studies and possible reasons for their findings.

A study by Holland et al. (2009) compared the costs of reducing transportation emissions through either a low carbon fuel standard (LCFS) or carbon pricing[33]. They report that the average abatement costs for an LCFS are large at \$307 to 2,272/tonne CO_2, as compared to \$60 to 868 for an economically efficient carbon pricing policy[34]. This amounts to an LCFS costing 2.5 to 5 times more than an economically efficient policy. They also report that in some circumstances an LCFS can increase net carbon emissions.

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[31] IEA. (2011). Technology roadmap: biofuels for transport. International Energy Agency. Paris, France.
[32] Ibid.
[33] Holland, S., Hughes, J. & Knittle, C. (2009). Greenhouse gas reductions under low carbon fuel standards? *American Economic Journal: Economic Policy 2009,* 1(1): 106-146. http://www.aeaweb.org/articles.php?doi=10.1257/pol.1.1.106
[34] Note that the LCFS they focus on is an ‘energy-based’ LCFS, which sets a requirement to reduce the average carbon intensity of fuels (the average emissions per unit of energy), relative to some pre-determined carbon intensity value. This is how LCFS policies are generally designed. The economically ‘efficient’ policy they use for comparison could represent either a carbon price or a ‘historical baseline’ LCFS, which sets a requirement to reduce the average carbon emissions of fuels per unit of historic energy production; that is, if the requirement is to reduce carbon intensity by 10% in 2030 relative to 2015, the required intensity would be that average emissions in 2030 divided by energy production in 2015 is 10% lower than the emissions intensity in 2015. For the purposes of the present report, when we discuss an LCFS we are referring to an ‘energy-based’ LCFS.

Fox et al. (2017) compared the costs of a carbon tax, a flexible technology neutral vehicle emissions standard (VES), and a technology-specific VES[35]. They found that the carbon tax cost was approximately one-third the cost of a flexible technology neutral VES.

Noel and Roach (2017) look at the costs of emission reductions resulting from an ethanol mandate in New South Wales, Australia[36]. The mandate required ethanol to be blended into gasoline at rates rising to 6% of fuel supply. They estimate that the mandate reduced gasoline emissions by only 1.2% at a cost of more than $1,200 per ton of carbon. They call the mandate 'exceptionally expensive', comparing it to the Australian Clean Air Regulator's permit price of $23 used in national efforts to reduce emissions. The $23 price was estimated to reduce emissions in Australia by 12%.

Chen et al. (2014) compare the costs of reduced US emissions using either carbon pricing, an LCFS, or a renewable fuel standard[37]. They find the carbon price to be significantly more economically efficient than the LCFS and renewable fuel standard. While all three policies increase US social welfare, the increase under the carbon price of $134 billion is several times larger than the increase of $33 billion under the LCFS and $47 billion under the renewable fuel standard.

Holland et al. (2013) examined the use of carbon pricing and an LCFS to reduce emissions in the US[38]. They find that the marginal abatement costs for a 10% reduction in emissions are $40/tonne for carbon pricing and $190/tonne for the LCFS.

All these studies paint a picture of regulations – whether they be ethanol or renewable fuel mandates, low carbon fuel standards, or vehicle emission standards – as being an expensive way to reduce emissions relative to carbon pricing. However, the results of any modeling study are a product of the assumptions and focus. Using different assumptions and exploring different questions could lead to different results. In the remainder of this section, we point out several restrictive and limited assumptions that appear to have contributed to the high costs of regulations estimated in these studies.

Lifecycle emissions of biofuels

Several studies assume fixed, high lifecycle emissions for biofuels. In their main scenarios, Holland et al. (2009) assume that ethanol lifecycle emissions are fixed at approximately 64 g CO_2e/MJ, or 75% of the emissions of gasoline. Fox et al. (2017) assume that ethanol lifecycle

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[35] Fox, J., Axsen, J, & Jaccard, M. Picking Winners: Modeling the Costs of Technology-specific Climate Policy in the U.S. Passenger Vehicle Sector. *Ecological Economics*, 137: 133-147. https://doi.org/10.1016/j.ecolecon.2017.03.002.

[36] Noel, M. & Roach, T. (2017). Marginal reductions in vehicle emissions under a dual-blend ethanol mandate: Evidence from a natural experiment. *Energy Economics* (2017). doi:10.1016/j.eneco.2017.01.011

[37] Xiaoguang Chen, Haixiao Huang, Madhu Khanna, Hayri Önal, Alternative transportation fuel standards: Welfare effects and climate benefits, Journal of Environmental Economics and Management, Volume 67, Issue 3, May 2014, Pages 241-257, ISSN 0095-0696, https://doi.org/10.1016/j.jeem.2013.09.006

[38] Holland, S., Hughes, J., Knittel, C. & Parker, N. (2013). Unintended consequences of transportation carbon policies: Land-use, emissions, and innovation. National Bureau of Economics Working Paper No. 19636. November 2013. http://www.nber.org/papers/w19636

emissions are fixed at 73 g/MJ, or 85% of the emissions of gasoline. Since each unit of ethanol results in only a small amount of emissions savings over gasoline, and ethanol production costs are higher than those of gasoline, it follows from these initial assumptions that switching to ethanol would be a costly way to achieve emission reductions.

For an LCFS, high lifecycle emissions for ethanol means that large amounts of ethanol are needed to meet a given intensity reduction. This implies that substantial costs must be incurred for the policy to achieve a small amount of emission reductions. In Holland et al.'s (2009) scenarios, when an economically efficient carbon pricing policy is used to achieve an equivalent amount of emission reductions, much less of the costlier action of switching to ethanol occurs, and instead emission reductions are achieved through reduced driving.

For a VES that requires a given percent of new vehicle sales to be low emission, and considers ethanol flex-fuel vehicles to be low emission, high lifecycle emissions for ethanol means that the VES requirement can be met by vehicle sellers while only reducing emissions by a small amount. In Fox et al. (2017), for example, ethanol vehicles dominate the sales of low emission vehicles required to satisfy the VES requirement. Since the study assumes that ethanol production processes will continue to achieve minimal lifecycle emission reductions relative to gasoline, this path is a costly way to reduce emissions even though it is the least cost way to satisfy the VES regulatory requirement. From a policy design perspective, this result highlights the need to ensure that the VES actually reduces emissions. If biofuel vehicles are included in a VES, either they should only be credited in proportion to the amount that biofuel reduces lifecycle emissions, or the VES should be paired with an LCFS that requires a declining lifecycle emissions intensity of biofuel production. Again, in the carbon pricing scenario, a large amount of emission reductions are achieved at a lower cost through reduced vehicle use, rather than through more costly adoption of low emission vehicles.

If biofuels can be produced in ways that achieve substantial lifecycle emission reductions relative to fossil fuels, this would reduce the cost of vehicle and fuel regulations. Indeed, Holland et al. (2009) run a sensitivity scenario that assumes lower lifecycle emissions for biofuels, and find that the cost difference between the LCFS and carbon pricing is significantly smaller.

Demand reduction for vehicle travel

In a number of the studies, a large portion of the emission reductions achieved under carbon pricing occur as a result of reduced demand for travel by vehicle, which could include switching to other modes of travel, such as public transit and cycling, or reducing distances travelled altogether. For example, in the Fox et al. (2017) carbon price scenarios, 73 to 85% of emission reductions were achieved through reduced vehicle travel rather than fuel switching.

If reducing vehicle travel is a low-cost way to reduce emissions, then substantial reductions in vehicle travel would occur in response to increasing fuel prices. Carbon pricing generally leads to larger increases in fuel prices than a flexible regulation like the LCFS, particularly at low to moderate levels of policy stringency. Carbon pricing involves government taxation of all emissions of low and high carbon fuels, increasing fuel prices accordingly. An LCFS involves no government taxation; rather, fuel prices of higher carbon fuels increase as a result of industry participants purchasing credits to offset any emissions above the required emissions intensity reduction, while fuel prices of lower carbon fuels decrease as a result of those industry participants selling the surplus credits they received for overshooting the required declining emissions intensity. A vehicle emissions standard has no direct effect on fuel prices. If carbon pricing – via larger increases in fuel prices – is better at realizing low-cost emission reductions from reduced vehicle travel, then it would be more economically efficient than regulatory policies.

While reducing vehicle travel is a low-cost option from a financial perspective, since other modes of transport generally cost less money per person kilometre travelled, it may be a higher cost option from a welfare perspective. Due to considerations of convenience, time, and status, many people see reducing vehicle travel as a high cost action. Various studies have found that vehicle travel is in fact relatively inelastic, that is, a relatively small amount of reduction in vehicle travel occurs in response to increases in fuel prices. For example, a literature review by Goodwin et al. estimates that a 10% increase in fuel prices would only lead to a 1% reduction in traffic volume in a year's time and a 3% reduction in about five years (elasticity of 0.1 to 0.3)[39]. Another literature review by Fearnley et al. similarly found that across many studies, a 10% increase in fuel prices was found to lead to on average a 2.5% increase in public transit use and a 1.1% increase in walking and cycling (elasticities of 0.25 and 0.11)[40]. These low elasticities suggest that reducing vehicle travel may have a high welfare cost for many people, and that unfounded assumptions that this will be the major response to carbon prices would result in an overestimate of the cost advantages of carbon pricing relative to flexible regulations for low-emission fuels and vehicles.

Policy stringency

Many studies focused on policies that are only applied at low levels of stringency. Holland et al. (2009) look at LCFS policies with intensity reduction requirements that only achieve between 1 and 10% reduction in average fuel emissions intensity. Noel and Roach (2017) look at an ethanol mandate that only increases the blend of ethanol by up to 6%. Holland et al. (2013) look at abatement costs for policies that only reduce total emissions by 10%.

The economic efficiency difference between carbon pricing and flexible regulations appears to be accentuated when applying policies with weak reduction requirements and low stringency. With increasing stringency, the economic efficiency difference between policies should decrease. To illustrate, consider the most stringent LCFS requirement – a 100% reduction in emissions intensity. In this case, all forms of energy used in transport must be zero emission (for simplicity, assume that fuels cannot have negative carbon intensities). The price of every zero-emission fuel would therefore simply be the production cost of that fuel as there would be no exchange of

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[39] Goodwin, P., Dargay, J. & Hanly, M. (2004). Elasticities of road traffic and fuel consumption with respect to price and income: A review. *Transport Reviews*, 24(3): 275-292. http://dx.doi.org.proxy.lib.sfu.ca/10.1080/0144164042000181725

[40] Fearnley, N et al. (2016). Triggers of urban passenger mode shift – state of the art and model evidence. Association of European Transport, 2016 European Transport Conference. https://abstracts.aetransport.org/paper/index/id/4792/confid/21

emission credits. People would respond to these fuel prices in typical ways, including purchasing vehicles that run on zero emission fuels, purchasing more energy efficient vehicles, and reducing travel by vehicle through mode shift and travel reduction.

Then consider a carbon price that achieves an equivalent amount of emission reductions – that is, a goal of zero emissions in transport. The carbon price would have to rise high enough so that all non-zero emission fuels are so expensive that demand for them falls to zero. When that carbon price is reached, the price of fuels consumed would again be simply the price of the fuels, since there would be no carbon charge applied to fuels like electricity, hydrogen and biofuels produced and consumed with zero-emissions. People would in turn respond to the fuel prices in the various ways mentioned above for the LCFS. At this stringency, the LCFS and carbon price would have identical effects – people facing identical price incentives should make identical choices, and the policies would perform the same in terms of economic efficiency.

In practive, either policy would be applied with increasing stringency over time, rather than jumping to zero emissions tomorrow. Thus, the two policies would result in somewhat different incentives over time for purchasing different vehicle types, leading to a somewhat different market composition of vehicles by the time the zero-emission objective was reached. Nevertheless, the zero-emission scenario is illustrative of how the economic efficiency difference of carbon pricing and flexible regulations should decrease with policy stringency.

Exploring policies that target deeper emission reductions should thus result in a smaller difference in costs between carbon pricing and regulations. For an LCFS, a more stringent intensity reduction requirement means that an increasingly greater proportion of the fuel emissions require offsetting through the purchase of credits from lower carbon fuels. The average price of fuels should move increasingly towards the economically efficient price under carbon pricing, in which all emissions are priced, and the incentive to respond through a variety of actions – fuel switching, energy efficiency improvements, and mode shifting – should be similar.

Policy flexibility

Some of the studies explore policies with limited flexibility. Holland et al. (2009) analyze an LCFS but only include ethanol as a low carbon fuel rather than also including other fuels such as electricity and hydrogen. The LCFS modeled in Chen et al. (2014) similarly only includes biofuels and not other low carbon fuel options.

The economic efficiency of a policy tends to increase if there are more options available for compliance. A flexible policy gives people and firms more choice in what actions they take to comply with the policy, thus enabling them to choose their lowest cost way to comply. In contrast, an inflexible policy requires compliance through a limited range of options. If the government knew in advance the lowest cost way to achieve a given emissions target, it could simply create an inflexible policy that required that action or set of actions to occur. However, since the government cannot know what the lowest cost set of actions will be, an inflexible policy may result in much higher costs to achieve an emissions target.

The question of whether a technology-specific or technology-neutral policy is preferable is complex. In some instances, an inflexible policy that forces early adoption of a likely winning technology, thus causing early decreases in its production cost, could be less costly than a flexible policy, as occurs in one of the scenarios in Fox et al. (2017). However, without perfect foresight by the policy designers as to which will be the winning technology, a flexible policy will be less costly. It follows that regulations designed to have more flexibility should reduce the cost difference between carbon pricing and regulations.

Emission reductions in transport

A few studies compare costs of two policies that achieve different amounts of emission reductions in transport. Noel and Roach (2017) compare the costs of an ethanol mandate that reduces emissions in transport by approximately 1% with an economy-wide emissions price that reduces emissions by 12%. They do not specify how much emission reductions the latter achieves in transportation. Fox et al. (2017) do not align their carbon pricing and regulatory scenarios to achieve the same amount of emission reductions in transport.

When considering the economic efficiency of a policy that only applies to one sector, there are two aspects of economic efficiency to consider. First, there is inter-sector efficiency, that is, whether the policy is achieving an appropriate amount of emission reductions in the sector in question, within the context of an economy-wide emission objective. Economically efficient policy would result in equal marginal abatement costs in all sectors, and thus the sector-specific policy should aim to align its marginal abatement costs with that of other sectors. Second, there is intra-sector efficiency, that is, whether the policy is achieving the amount of emission reductions within a given sector in an economically efficient manner.

When comparing a sector-specific flexible regulation to carbon pricing, the carbon price should be achieving the same amount of emission reductions as the regulation in that sector in order to enable measurement of intra-sector efficiency. If the carbon price is achieving fewer emissions reductions than the regulation in question, the costs of the regulation may be higher partially due to differences in policy ambition. Perhaps the regulation in question would be adopted together with regulations in other sectors that together achieve substantially more emission reductions than the carbon price at the level in question. In that case, the costs of the regulation would be justifiably higher than the carbon price. Thus, a more accurate indication of the relative economic efficiency of carbon pricing and a sector-specific flexible regulation is if the two policies are compared when they achieve the same amount of emission reductions in the sector.

Social and environmental impacts of biofuel production

Some studies include the costs of social and environmental impacts in their calculations of the societal costs of policies that lead to increased biofuel production. Chen et al. (2014) assume that increased biofuel production will increase food prices considerably and reduce global welfare. Holland et al. (2013) assume that increased biofuel production will increase habitat loss and fertile land erosion.

If a policy like an LCFS were to lead to substantially more biofuel production than carbon pricing, and if it is assumed that biofuel production has substantial social and environmental costs, then an LCFS would be a higher cost policy than carbon pricing. Note, however, based on the discussion above, that unless we assume low welfare costs for reduced vehicle travel, an LCFS should not result in substantially more biofuel production than a carbon price that achieved comparable emission reductions. And, as noted above, there may be potential to produce substantial amounts of biofuels in a sustainable manner without major impacts on ecosystems and food prices. If so, a moderate amount of biofuel production can occur without substantial social and environmental costs, and a flexible regulation like an LCFS would have lower costs than some studies have suggested.

Elasticity of fossil fuel supply

Finally, we address the finding in Holland et al. (2009) that an LCFS could increase net emissions compared to a situation in which there was no policy whatsoever. Industry compliance with an LCFS average intensity reduction involves cross-subsidies between industry participants, as retailers of higher carbon fuels purchase credits from retailers of lower carbon fuels. Holland et al. explain that rising net emissions could occur if emissions from increased production of the lower carbon fuels outweigh emissions from reduced production of higher carbon fuels that pay the subsidies. Increasing net emissions occurs in only one of their eighteen simulations, an increase of 0.1%. This outcome requires a unique combination of four restrictive assumptions: inelastic gasoline supply (elasticity = 0.5), highly elastic ethanol supply (elasticity = 4.0), very weak LCFS reduction requirement (1% reduction in average fuel carbon intensity), and ethanol lifecycle emissions only slightly lower than gasoline (0.75 that of gasoline).

To understand how emissions could possibly increase with a policy that targets emission reductions, we test slightly more extreme assumptions. First, assume perfectly inelastic gasoline supply (a vertical supply curve). This means that gasoline producers would lower their prices whatever amount was necessary to ensure that they sold the exact same amount of gasoline before and after imposition of the LCFS policy. At the same time, increasing amounts of ethanol must be sold, so that average carbon intensity declines as required by the policy. Since this ethanol is being produced and consumed *in addition* to the amount of gasoline that was being produced and consumed previously and will be produced in future (with a vertical supply curve), and if it is also assumed that ethanol production has almost as many lifecycle emissions as gasoline (as in the case of Holland et al, 2009), net emissions would increase.

But for this scenario to occur under increasing LCFS stringency, gasoline producers would need to lower their retail prices while simultaneously facing higher costs to buy credits that subsidize ethanol producers. In this economically implausible circumstance, the increasing sale of total fuels would offset the increasing sale of biofuels, such that net emissions increased.

While Holland et al.'s scenario does not assume a perfectly inelastic gasoline supply, it assumes a very low elasticity and a very weak LCFS reduction requirement. As soon as the LCFS stringency is increased to require a 5% reduction in emissions intensity, total emissions start to fall. Thus, except in this unlikely, extreme case, this flexible regulation won't increase net emissions relative to what would have occurred without the policy.

4. A Clean Fuel Standard for Canada's Transport Sector: Scenarios

In the previous section, we explained why assumptions of some studies have led them to find high costs of flexible transport regulations relative to carbon pricing, related to both the cost-effectiveness of biofuels as a key action for reducing emissions and the cost-effectiveness of flexible regulations as the dominant policy tool. In this section, we outline our current modeling exercise in which we apply different, and in our view more plausible, assumptions about actions and policy design in the transport sector.

Reference Scenario

The *Reference Scenario* serves as a point of comparison for how emissions would progress in the absence of additional policy efforts. It includes those elements of the Pan-Canadian Framework released in December 2016 for which we have sufficient detail to model them, as follows:

- **Federal backstop carbon price:** a carbon price in all provinces starting at $10 in 2018 and rising to $50 by 2022. The federal government has not yet provided information about increases in its backstop carbon price after 2022, and thus we leave it frozen at $50 after 2022. The announced carbon price is a nominal price rather than indexed to inflation, which means that the $50 declines in real terms over time. While the federal backstop price may in future be exceeded by some provincial carbon prices, for consistency and simplicity, we model only the federal backstop price in all provinces.
- **Coal phase out:** all coal-fired electricity generation that is not retrofitted with carbon capture and storage is eliminated by 2030
- **Methane regulation in oil and gas:** methane emissions from the oil and gas sector are reduced by 40 to 45 percent from 2012 levels by 2025

In our reference scenario we also include major federal and provincial climate policies that were in place or announced prior to the release of the Framework, as follows[41]:

- **Federal:** light-duty and heavy-duty vehicle emissions standards, which set minimum emissions standards for vehicles up to 2025; performance standard for new and end-of-life coal plants, which requires them to meet an emissions-intensity standard equivalent to natural gas plants (in essence requiring end-of-life coal plants to either shut down or retrofit with carbon capture and storage technologies).
- **British Columbia:** clean electricity regulation, which requires 100% of electricity generation in the province to be from clean or renewable electricity (with allowances to address reliability).

[41] We do not include provincial carbon pricing policies since we apply the federal backstop carbon price to all provinces.

- **Alberta:** a commitment to replace two-thirds of phased-out coal capacity with renewable energy capacity; a performance standard for oil sands operations to ensure that oil sands emissions remain under the 100 Mt cap.
- **Saskatchewan:** the Boundary Dam coal power plant carbon capture and storage retrofit; target of 50% renewable electricity capacity by 2030.
- **Manitoba:** phase out of coal electricity generation that was completed in 2010.
- **Ontario:** phase out of coal electricity generation that was completed in 2014; feed-in-tariff that offered fixed contract prices for renewable generation and is being transitioned to include a procurement process for larger renewable electricity projects.
- **Quebec:** zero-emissions vehicle mandate, which requires automakers to sell a minimum number of near zero-emissions vehicles, increasing to 15.5% of sales by 2025.
- **Atlantic:** Nova Scotia's declining electricity sector emissions cap, which required the combined emissions of all electricity-producing facilities in the provinces to be no greater than 4.5 Mt CO_2 by 2030; Nova Scotia's renewable portfolio standard, which requires a minimum of 40% renewable generation by 2020.

Also included are all provincial and federal low carbon and renewable fuel standards, energy efficiency standards in provincial building codes, federal energy efficiency standards for energy-consuming technologies, and provincial landfill gas regulations. We have not modeled subsidy and incentive programs, as these do not guarantee emissions reductions, are prone to high levels of free-ridership (i.e. subsidies are claimed by those who would have purchased the technology even in the absence of the subsidy), and often only last for limited durations[42].

Carbon Pricing – Achieve Paris Scenario

The *Carbon Pricing – Achieve Paris Scenario* is designed to serve as comparison with our CFS policy scenarios. It relies on a steadily rising economy-wide emissions price to achieve Canada's 2030 Paris commitment to reduce emissions by 30% below 2005 levels, and then continues reducing emissions to reach 65% national reductions by 2050, in line with Canada's targets[43]. The carbon price is applied to both fossil fuel combustion emissions and non-combustion industrial process emissions. It could represent either a carbon tax or the effect of permit trading on fuel prices in a cap-and-trade system. The carbon price is additional to all other climate policies (regulations and subsidies) from the *Reference Scenario*.

We assume that carbon price revenues are recycled in the form of lump sum payments to the sector from which the revenue was collected, achieved in a way that would not mute the policy's effect on emission prices. This helps minimize policy-induced transfers among provinces, industrial sectors and individuals. We also assume that if adopting a stringent carbon price,

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[42] For example, see Linares, P. and Labandeira, X. (2010), Energy efficiency: Economics and policy. *Journal of Economic Surveys*, 24: 573–592. doi:10.1111/j.1467-6419.2009.00609.x

[43] For example, see National Round Table on the Environment and the Economy. (2007). Getting to 2050: Canada's Transition to a Low-emission Future. Available at: http://nrt-trn.ca/wp-content/uploads/2011/08/Getting-to-2050-low-res.pdf

Canada would implement trade measures to protect its domestic industries and minimize leakage if its trading partners do not adopt comparably stringent policies.

Clean Fuel Standard Scenarios

We run scenarios with a clean fuel standard (CFS) that in all cases is applied exclusively to the transport sector. Except where otherwise noted, the CFS is modeled in addition to the policies in the *Reference Scenario*, including the backstop federal carbon price[44].

A CFS requires a fuel carbon intensity reduction that must be met on average for all fuels covered by the policy. It applies to the producers or retailers of the fuels. Those producers or retailers for whom the average carbon intensity of the fuels they sell exceeds the CFS reduction must purchase compliance credits from producers or distributors of fuels with carbon intensities below it. In this way, a CFS produces cross-subsidy payments between producers or retailers whose fuels have carbon intensities above and below the CFS requirement at a given time. The policy thus differs from conventional carbon pricing, which in its ideal form, taxes the fossil fuel-derived carbon emissions of any fuel, no matter how small its carbon intensity[45].

The formula we use to determine the credits or debits that a unit of a given fuel generates is as follows:

Credits or Debits = Carbon Intensity Requirement x EER – Fuel Carbon Intensity

If the value is positive, the fuel generates credits which the low intensity supplier can sell to high intensity suppliers, thereby receiving a cross-subsidy from them. If the value is negative, the fuel generates debits which the high intensity supplier must offset by purchasing credits from low intensity suppliers. The energy effectiveness ratio (EER) is used to account for the fact that some fuels are more energy efficient than others in providing an equivalent transportation service. For example, an electric vehicle, with its highly efficient electric motor, requires fewer units of energy per kilometer compared to an equivalent-sized gasoline vehicle, with its relatively inefficient internal combustion engine. For this study, we use an EER of 1.2 for diesel and 2 for electricity, estimated based on EER values used in the BC LCFS and the vehicle energy efficiencies used in our model[46]. The price for credits at a given time is based on the trajectory required to meet the declining fuel carbon intensity reduction under the CFS policy.

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[44] When applying a package of policies, it is important to consider possibly interactions of those policies. If a CFS or other regulations are applied in a jurisdiction with a cap-and-trade system, such as in Ontario and Quebec, it is possible that the regulation would not lead to additional emission reductions but rather shift reductions among sectors, if the cap is binding. However, if the credit price is at the floor price (i.e. the cap is not binding), then the regulation could lead to additional emission reductions. For our scenarios, we assume that the federal backstop price is the new floor price for Ontario and Quebec, which means that the CFS could be additive.

[45] An ideal carbon price would ensure that the full lifecycle emissions of a fuel are taxed at some point during the fuel's lifecycle. If the carbon price already applies to fuel production sectors, then the carbon price applied directly to the fuel need only apply to combustion emissions and perhaps also direct land use emissions.

[46] While the EER for electricity is higher under current LCFS policies (for the BC LCFS, it is 3.0; for the California LCFS, it ranges from 2.7 to 4.6 depending on the transport mode), we use an EER value of 2 due to the data and assumptions in our model. For personal vehicles, we assume that between 2020 and 2030, the current federal vehicle efficiencies standards require all new personal gasoline vehicles to approach the efficiency of current hybrid

We apply the CFS as an average carbon intensity requirement for all transport fuels. That is, the policy applies to a single pool that includes all fuels used by all modes of personal and freight transport, including cars, trucks, buses, trains, and airplanes. Fuels include gasoline, diesel, biofuels, electricity, hydrogen, natural gas, and jet fuel. This wide policy coverage maximizes the policy's flexibility. We also assume that mechanisms are created so that the implicit price signal of the policy reaches final consumers. Thus, if electric utilities are generating credits for sales of electricity to plug-in electric vehicle (PEV) owners, the savings would be passed on to the PEV owners, such as through lower electricity rates when using PEV recharging devices.

Carbon intensities for refined petroleum products and natural gas are fixed, which we estimated from a combination of the fixed carbon intensities under the BC LCFS and the carbon intensities in the GHGenius 4.03a model (see Table 2)[47]. Set carbon intensities were used for these fuels since ECCC has indicated an intent to not differentiate between crude oil types produced in or imported into Canada[48]. Carbon intensities for electricity are based on the emissions intensity of electricity generation in the model, which varies by province, over time, and according to the policies applied to that sector. Carbon intensities for biofuels are presented in Section 5.2.

Table 2. Lifecycle carbon intensity values used for fossil fuels

Fuel	Carbon Intensity (g/MJ)
Gasoline	87
Diesel	94
Natural gas	59
Jet fuel	97
Propane	71
Heavy fuel oil	90

Carbon intensity reductions are measured as a percent reduction relative to a baseline value. We set the baseline as the carbon intensity in 2015, as calculated within our data-rich energy-economy model, CIMS. This value of 80.4 g/MJ is lower than the Table 2 emissions intensities of both gasoline and diesel due to a combination of using an EER of 1.2 for diesel and the required blending of biofuels, recorded in CIMS, into gasoline and diesel as per Canada's current federal and provincial renewable fuel regulations. The CFS scenarios we ran are the following:

vehicles. In our model, a large hybrid car consumes 1.85 MJ of gasoline per km, while an electric vehicle consumes 0.90 MJ of electricity per km. A standard efficiency light freight truck consumes 7.5 MJ of diesel per km, while an electric light freight trucks consumes 4 MJ of electricity per km. The resulting average EER of these two modes is approximately 2, and we apply this EER to electricity for all transport modes as a simplification. Note that we use an EER of 1 for hydrogen, again an average value based on the relative energy efficiencies in our model.

[47] (S&T)2. (2013) GHGenius, Model Version 4.03a; (S&T)2 Consultants Inc. for Natural Resources Canada: Delta, British Columbia

[48] Environment and Climate Change Canada. (2017). Clean Fuel Standard: Discussion Paper. Available at: https://www.ec.gc.ca/lcpe-cepa/default.asp?lang=En&n=D7C913BB-1

- ***Proposed Federal CFS Scenario*****:** In its discussion paper on the proposed CFS, ECCC has indicated it is considering carbon intensity reductions of approximately 10 to 15% by 2030[49]. We thus run two versions of the proposed CFS:
  A) Proposed Federal CFS – 10%: achieves a 10% reduction by 2030, and
  B) Proposed Federal CFS – 15%: achieves a 15% reduction by 2030.
  We extend the intensity reductions through our simulation to 2050 with CFS values of approximately 25% reduction and 30% reduction respectively for the two versions.

- ***Efficient CFS Scenario*****:** In this scenario, we find the carbon intensity reduction that would require the transport sector to achieve its same emission reductions as in the *Carbon Pricing – Achieve Paris Scenario*. We run two version of this scenario:
  A) Efficient CFS – Ref Scenario: the low federal carbon price from the *Reference Scenario* is run in all sectors. The transport sector achieves its economically efficient contribution to the Paris target, but Canada falls far short of the Paris commitment.
  B) Efficient CFS – Achieve Paris Scenario: the high federal carbon price from the *Carbon Pricing Scenario* is run in sectors outside of transport to achieve their economically efficient contributions to the 2030 Paris target and the 65% 2050 target. While we model a carbon price for these policies in other sectors, they could be flexible regulations instead. We maintain the backstop federal carbon price from the *Reference Scenario* in the transport sector and add our CFS requirements.
  The reason for running two versions of this scenario is that what is occurring in other sectors impacts the required emission reductions in the transport sector. For example, the strength of policy in the electricity sector will impact the carbon intensity of electricity used for fueling PEVs. As another example, strong policy in industrial and manufacturing sectors may lead to somewhat slower growth in overall economic activity, thus requiring less freight transport.

- ***CFS without Carbon Pricing – 10% Scenario*****:** For comparative purposes, we run a scenario that includes a 10% CFS intensity reduction in transport but in which there is no carbon pricing in any sector throughout Canada. Our purpose is to estimate an emissions reductions value that by comparison to the *Proposed Federal CFS – 10% Scenario,* which includes carbon pricing, provides an indication of incremental policy effects.

5. Modeling Method

5.1. Model Description

Analysts apply energy-economy models to estimate the likely impact of policies focused on the transition to low- and zero-emission energy options. 'Computable general equilibrium' (CGE) models have some sectoral and technological details, but especially focus on the macro-economic links between private and public investments and expenditures, and government budgets, making them ideal for modeling the revenues and expenditures triggered by an

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[49] Ibid.

economy-wide carbon tax. In contrast, 'hybrid energy-economy' models have some macro-economic feedbacks, but especially represent the technology acquisition and fuel use decisions of firms and households in energy demand sectors (transportation, buildings, energy consuming industries) and energy supply sectors (oil, gas, electricity, renewables). While CGE models are good at estimating the GDP effects of emissions pricing policies, hybrid models are good at estimating the combined effect of technology- and sector-specific policies designed to regulate or otherwise influence technology and energy choices.

Given that our key scenarios involve a CFS, which focuses on specific transport fuels and the vehicle technologies that use them, we opted to use a well-known hybrid energy-economy model to simulate our policy scenarios. This model, called CIMS, was developed by researchers in our institute over the past three decades, but is now widely used across Canada and in other countries[50]. It has similarities to the NEMS model used by the US Energy Information Administration to estimate the effect of energy-climate policies in that country.

CIMS simulates technology and energy choices based on conventional and less conventional investment attributes. Conventional attributes include capital cost, non-energy operating cost, energy cost, and time preference. Less conventional attributes include technology- and energy-specific risks and firm and household intangible preferences, as estimated from revealed data (historical market decisions) and stated data (survey responses when asked hypothetical question – about for example an electric car), or as estimated through expert judgement.

CIMS is also designed to pick up dynamic feedbacks that reflect how financial costs and intangible factors may change over time. As new technologies pass market thresholds, their costs of production fall to reflect economies-of-scale in manufacture and more intensive innovation. At the same time, as new technologies gain market share, a 'neighbor effect' function in the model reflects how resistance to new technologies decreases because potential consumers become more familiar and confident with the product as more neighbors and friends adopt it.

While CIMS offers these strengths as a policy simulation tool, it lacks the ability to estimate the broader macro-economic effects where government policies change the tax regime. Thus, if governments apply a carbon tax, CIMS can simulate the emissions effect of the carbon tax, but it cannot show the relative GDP effect of alternative revenue recycling schemes, such as income tax cuts, lump sum payments, subsidies to energy transition investments, and public infrastructure investments. In using CIMS in this exercise, therefore, we assume for expediency that government recycles carbon tax revenues (and other climate related charges) so that redistribution effects among regions, sectors and individuals are minimized. Often, this assumption is a valid depiction of the utilization of much of the revenues from real-world emission pricing regimes.

CIMS is also less effective than a CGE model at estimating structural effects as climate policies increase the production costs in some sectors more than others. The version of the model that we

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[50] For details on key CIMS algorithms and assumptions, see Jaccard, "Combining top-down and bottom-up in energy-economy models," in Evans and Hunt (eds.), International Handbook on the Economics of Energy, Edward Elgar, 2009.

apply in this project does estimate some structural change in response to changing relative costs of production, but this factor is incomplete compared to a typical CGE model. We note again, however, that in designing climate policies, including carbon taxes and cap-and-trade, governments seek to minimize structural effects on the economy.

Since CIMS underrepresents structural and GDP changes resulting from climate policies, especially as these policies become more stringent, it exaggerates the emissions price necessary to achieve a given level of emissions reductions. In other words, emissions fall under a rising carbon price because people switch fuels and use less energy, and CIMS captures this. But emissions also fall because emissions-intensive industries and activities, and even total economic output, decline. With its partial equilibrium view, CIMS might show that a tax of \$100/tCO_2 is needed for a 20% emissions reduction. With a full equilibrium view, a CGE model might show that only \$85/tCO_2 is needed for the same 20% reduction, because that model includes the additional, simultaneous reductions caused by structural and output changes.

Fortunately, our modeling team has considerable experience using CGE models and CIMS, both alone and in tandem, for estimating the structural and total output effects of climate policies[51]. Based on this previous work, we adjust our CIMS carbon price estimates to correct for this missing modeling element. We assume that the carbon price required to achieve a given emissions reduction objective in a CIMS simulation is about 1.25 times the carbon price that would actually be required to achieve that objective. Thus, if a carbon price of \$125/tonne is required in a CIMS simulation to achieve an objective, we report the required carbon price as \$100. Conversely, if the government is adopting a \$10 carbon price, we run a \$12.5 carbon price in CIMS. All carbon prices reported in our results section are the corrected values.

Strong regulations can cause structural changes in the same way that strong carbon prices can. In transport, the amount of freight transport may fall if strong policy leads to slower economic growth. Therefore, in all our CFS scenarios, we assume that emissions in freight are 1.5% lower in 2030 and 3% lower in 2050 than the emissions value that CIMS produces. The emissions values reported in our results also have this adjustment.

5.2. Modeling Data and Assumptions

This section outlines key assumptions and data sources used for the modeling. We focus on model parameters in the transport sector given the focus of this study on transport.

Sector Activity Levels

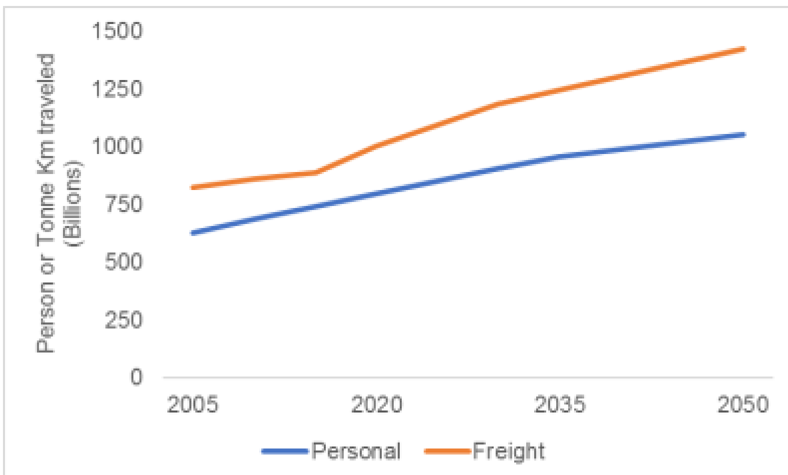
The projections in CIMS are driven by sector activity levels, which specify the levels of demand, production or other activity in each sector. The activity levels drive technology acquisition, energy consumption, and thus emissions.

Figure 1 shows the baseline total national activity level trajectories used for personal and freight transportation. For personal transport, annual growth rates are on average 1.4% from 2015 to

[51] See for example Peters, Bataille, Rivers and Jaccard, (2010) "Taxing emissions, not income: How to moderate the regional impact of federal environment policy," CD Howe Institute.

2030 and 0.8% from 2030 to 2050. For freight transport, annual growth rates are on average 2.1% from 2015 to 2030 and 0.9% from 2030 to 2050. The personal transport forecast was calculated using provincial populations forecasts from Statistics Canada and using the assumption that a 1% increase in population corresponds to a 1.5% increase in person kilometers traveled, as has been the trend over the past 15 years. The freight transport forecast is set with demand for freight growing at a rate higher than the growth rate of demand for personal transportation, as is forecasted to occur by organizations such as the National Energy Board[52]. During simulation runs, elasticity of demand parameters within CIMS may modify the baseline activity level forecasts depending on the policy's effect on costs.

Figure 1: Sector Activity Level Assumptions for Personal and Freight Transport



Although not directly related to transport, assumptions about oil sands production are an important factor in determining emissions levels for Canada and the amount of emissions reductions that will be needed in other sectors to meet emissions reduction objectives. We assume a moderate growth forecast for oil sands production, rising from current production levels of 2.5 million barrels per day (mbd) to 4.25 mbd in 2030, and holding constant at that level through to 2050.

Fuel Prices

We set moderately rising price trajectories for gasoline and diesel, which rise at a rate that is half the rate of increase assumed in the Reference Scenario from the National Energy Board's *Canada's Energy Future 2016* report[53]. This assumption would align roughly with WTI oil prices rising to $65 per barrel by 2020 and $75 per barrel by 2040. Baseline electricity prices are also based on the Reference Scenario, and then CIMS adjusts them based on demand and costs of production within the model, which can vary based on the policies included in each scenario. Both high emitting and near-zero emission electricity production options are available. Table 3

[52] National Energy Board of Canada. (2016). Canada's Energy Future 2016: Energy Supply and Demand Projections to 2040. Retrieved from https://www.neb-one.gc.ca/nrg/ntgrtd/ftr/2016/index-eng.html
[53] Ibid.

shows the average prices for gasoline, diesel, and electricity in our *Reference Scenario*, prior to adding any carbon pricing.

Liquified natural gas, compressed natural gas, and hydrogen prices are also determined within the model based on energy prices, with the option to produce hydrogen using either higher emission natural gas-based steam methane reforming or lower emission electricity-based electrolysis[54]. Given that biofuels are one of the focuses of this study, we outline assumptions about biofuel prices in more detail in the following section.

Table 3: Average Fuel Prices for Gasoline, Diesel, and Electricity in *Reference Scenario*

	Price ($2015/L for gasoline and diesel, $2015/kWh for electricity)		
	2020	*2035*	*2050*
Gasoline	1.21	1.35	1.37
Diesel	1.33	1.47	1.50
Electricity	0.13	0.15	0.15

Note: Prices are an average of all Canadian provinces and are shown prior to any carbon pricing being added to the price.

Biofuel Emissions and Costs

We include five representative pathways for biofuel production: conventional ethanol produced from corn, cellulosic ethanol produced from corn stover, conventional biodiesel produced from canola, hydrogenation-derived renewable diesel produced from canola, and biomass-to-liquids renewable diesel produced from wood residues. While biofuels can be produced through many different pathways from a wide variety of feedstocks, we chose these five pathways as representative of general first and second generation gasoline and diesel replacements. Note that as second generation biofuels, cellulosic ethanol and biomass-to-liquid biodiesel are not available in the model until 2021.

We include the option for each biofuel pathway to be produced using high or low emission fuels. We assume that tractors and trucks used to produce, collect, and transport feedstocks can be fueled with either diesel or biodiesel, and we assumed that boilers used in the process of turning feedstocks into biofuels can be fueled by either natural gas or biomethane. Electricity produced as a co-product may also be used in the biofuel production process. We also include fuel consumption required for fertilizer production and direct land use emissions. Energy

[54] Assumptions for production of electricity, LNG, CNG, and hydrogen are the same as those used in Vass, T. (2016). Trading off political acceptability and economic efficiency: Policy options for reducing Canada's electricity and transportation emissions. Simon Fraser University, Masters Major Research Project. Available at: http://summit.sfu.ca/item/16942#310

consumption and land use emissions values were calculated based on data from the GHGenius 4.03a model, a transport fuel lifecycle assessment model developed in Canada[55].

Table 4 shows the energy consumption data and the resulting emissions of each biofuel production pathway. The first three columns show fuel consumption throughout the various stages of biofuel production (as noted above, diesel or biodiesel used to produce, collect, and transport feedstocks; natural gas or biomethane used in boilers that turn feedstocks into biofuels, as well as to produce fertilizer; and electricity used in biofuel production facilities). The fourth column shows land use emissions. The final four columns show total production emissions for each biofuel pathway, assuming different combinations of higher and lower consuming fuels used in the production process. The values are the sum of emissions from either diesel or biodiesel, either natural gas or biomethane, electricity, and land use. Emissions are shown both in terms of absolute emissions and the percent reduction relative to the lifecycle emissions of gasoline or diesel.

Table 4: Biofuel Energy Consumption and Emissions Assumptions

Biofuel	Fuel Consumption (MJ consumed/MJ fuel produced)			Direct Land Use Emissions (g/MJ)	Total Emissions (top = g/MJ, below = % reduction from gasoline or diesel)			
	Diesel or Biodiesel	*Natural Gas or Biomethane*	*Electricity*		*Diesel + Natural Gas*	*Diesel + Biomethane*	*Biodiesel + Natural Gas*	*Biodiesel + Biomethane*
Conventional Ethanol	0.051	0.383	0.034	12.7	40 54%	17 80%	35 59%	13 85%
Cellulosic Ethanol	0.106	0.228	-0.024	6.7	30 65%	17 81%	20 76%	7 92%
Conventional Biodiesel	0.017	0.067	0.009	8.8	14 85%	10 89%	13 86%	9 91%
HDRD	0.029	0.150	0.017	15.4	27 71%	18 81%	24 74%	16 84%
Biomass-to-liquids Diesel	0.016	0.003	-0.065	2.8	4 95%	4 95%	3 97%	3 97%

Note: Electricity production values represent net electricity consumption, after taking into account any co-produced electricity that is then consumed in the production process; negative values mean that surplus electricity is produced. When calculating total emissions, assumed lifecycle emissions for fuels are as follows: diesel = 94g/MJ, biodiesel = 2.8 g/MJ, natural gas = 59 g/MJ, biomethane = 0 g/MJ, electricity = 0 g/MJ. Within CIMS, electricity emissions vary based on the way electricity is generated within the model in each Canadian province.

Retail prices for biofuels are the sum of production costs, marketing and refinery margins, and taxes. We chose a middle-ground estimation for current and future biofuel production costs for each pathway based on a review of cost estimates cited in several different sources[56]. The actual

[55] (S&T)2. (2013) GHGenius, Model Version 4.03a; (S&T)2 Consultants Inc. for Natural Resources Canada: Delta, British Columbia.
[56] Sources include: Cazzola, P. (2013). Production costs of alternative transportation fuels: Influence of crude oil price and technology maturity. International Energy Agency. Paris, France; Chum, H. et al. (2011). Ch.2 – Bioenergy and Annex III. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation

production costs in the model are centered around these estimates but depend on fuel prices and thus vary over time, by province, and by the fuels used. We assume refining and marketing margins and fuel transport costs of $0.24/L for ethanol-85 and $0.14/L for biodiesel and renewable diesel. These estimates are approximations based on current retail prices for biofuels. Taxes are based on tax data for gasoline and diesel from Natural Resources Canada[57]. Fuel excise taxes average approximately $0.26/L for gasoline and $0.20/L for diesel; GST, PST, and HST are also applied on top of the excise taxes as appropriate[58]. Table 5 shows the resulting average current and future production and retail costs for each biofuel pathway, with retail costs shown for both higher lifecycle emission (produced with diesel and natural gas) and lower lifecycle emission (produced with biodiesel and biomethane) production methods.

Table 5: Biofuel Average Current and Future Production Costs and Retail Prices for

Biofuel	Production Costs ($2015/Leq)		Retail Prices ($2015/Leq)			
	Current	At Maturity	Current		At Maturity	
	Diesel + Natural Gas	*Diesel + Natural Gas*	*Diesel + Natural Gas*	*Biodiesel + Biomethane*	*Diesel + Natural Gas*	*Biodiesel + Biomethane*
Conventional Ethanol	0.98	n/a	1.62	1.78	n/a	n/a
Cellulosic Ethanol	1.33	0.98	2.00	2.16	1.62	1.77
Conventional Biodiesel	1.15	n/a	1.67	1.70	n/a	n/a
HDRD	1.34	1.15	1.87	1.95	1.67	1.74
Biomass-to-liquids Diesel	1.53	1.26	2.08	2.10	1.79	1.81

Note: Costs are an average for all Canadian provinces, and may vary in the model depending on prices of fuels used in producing the biofuels. Costs and price are given in liters per gasoline equivalent for ethanol and liters per diesel equivalent for biodiesel, assuming energy content of 35 MJ/L for gasoline and 38.3 MJ/L for diesel.

When evaluating the costs of biofuel production, an important consideration is what amount of feedstock can be produced at reasonable costs. Large quantities of production would likely at some point lead to rising feedstock costs, due to factors such as competition for land, using more land with lower bio-productivity, and increased costs of transporting feedstocks from remote areas to production facilities. Hoogwijk et al. (2009) conducted a global study of the potential for energy crops at various price cut-offs[59]. The study examined the production potential on

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[O. Edenhofer, et al. (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.; Sims et al (2010), An overview of second generation biofuel technologies, Bioresource Technology, 101(6): 1570-1580.; Turkenburg, W. C., et al. (2012). Chapter 11 - Renewable Energy. In Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 761-900.

[57] Natural Resources Canada. (2016). Fuel consumption taxes in Canada. Available at: http://www.nrcan.gc.ca/energy/fuel-prices/18885

[58] We apply taxes for biofuels on a volumetric basis, as currently occurs in Canada. However, we note that due to the lower energy density of biofuels, particularly ethanol, it may be more appropriate to tax biofuels based on energy content.

[59] Hoogwijk et al. (2009), Exploration of regional and global cost–supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. Biomass and Bioenergy, 33:26-43.

abandoned agricultural land and at-rest land in 2050 for four IPCC land-use scenarios, by region[60]. The study uses the term geographical land to refer to the total amount of biofuels that could be produced on available land in the region if there were no cost constraints. On average for the four scenarios, approximately 45% of geographical potential production is between $1 to 2/GJ, and 70% below $4/GJ. For Canada, 71% of geographical potential production is between $1 to 2/GJ, and 82% below $4/GJ (Table 6). The result is a relatively flat feedstock supply curve for a considerable amount of biofuels, which only at high levels of production then begins to rise.

Using the study's estimation of how the global feedstock potential translates into production costs of transport fuels and extrapolating for Canada's production potential, approximately 6.4 EJ of transportation biofuels could be produced in Canada within the $10 to 15/GJ range, which would be approximately $0.40 to 0.60/L for renewable diesel[61]. This amount is over twice the total amount of transport fuel currently consumed in Canada. Similarly, The Global Energy Assessment (2012) shows a relatively flat global supply curve for feedstocks from crop residues, municipal solid waste, and animals wastes, with most costs in the $2 to 3/GJ range[62]. Based on these findings, for our study we assume an essentially flat supply curve for biofuels, with pricing remaining as noted in Table 5 throughout the simulation period. Had our biomass demand estimates exceeded these potentials, we would then have assumed a rising supply curve.

Table 6: Hoogwijk et al.'s (2009) Estimation of Potential for Energy Crop Production for Canada in 2050 on Abandoned Agricultural Land and At-rest Land, Total and with Economic Cut-offs

	Production potential (EJ/year)			
	<$1/GJ	*<$2/GJ*	*<$4/GJ*	*Geographical potential*
High	0	11.4	14.3	18
Low	0	7.9	9.4	12
Average	0	10.1	11.7	14
% of geographical potential (for Average)	0%	71%	82%	100%

Note: the study includes four IPCC land-use scenarios. Displayed here are the highest, lowest, and average estimates from those four scenarios.

In our modeling, we also include intangible costs for biofuels, given the current lack of re-fuelling infrastructure and that they are less familiar fuels. We set these costs based on a

[60] Definitions of land types in this study are as follows: 'Rest land: includes all the remaining non-productive land that can be used for energy crop production. The rest land category excludes bioreserves, forest, agricultural and urban areas and is calculated after satisfying the demand for food, fodder and forestry products. Abandoned agricultural land: The agricultural land not required after satisfying the demand for food, fodder and forestry products. As such it is the land taken out of agricultural production due to less demand, higher land productivities elsewhere or both.'

[61] The study assumes a conversion efficiency from biomass feedstock to biofuels of 55%.

[62] Figure 7.25 in the GEA (2012). Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

combination of calibrating to current levels of biofuel consumption in Canada (which are close to zero apart from blending to meet renewable fuel mandates) and our judgement based on the nature of each fuel. Ethanol-85 and conventional biodiesel intangible costs are higher than those of renewable diesel since they would require a separate fuel tank and pump at refueling stations, whereas renewable diesel is a drop-in fuel that can simply be blended into conventional diesel in any amount in the refinery or at some stage post-refinery. All intangible costs decline relatively quickly with increasing uptake to reach relatively low levels. Table 7 shows the intangible cost assumptions we use.[63]

Table 7: Biofuel Intangible Cost Assumptions

Biofuel	Intangible Costs ($2015/Leq)	
	Initial	*Lowest*
Ethanol	0.51	0.10
Biodiesel	0.67	0.11
Renewable Diesel	0.44	0.11

Vehicle Costs

In CIMS, capital costs for personal vehicles are divided into the costs of the vehicle body and the cost of the motor. Each vehicle body demands a given amount of motor services, which can be met by different motor types. The motor capital costs in the model used for this study were estimated based on a combination of advertised manufacturer's vehicle sales prices in 2016 and estimates of vehicle technology costs in reports from the U.S. National Research Council and the MIT Laboratory for Energy and the Environment[64]. Costs for electric and plug-in hybrid vehicles were set to align with the assumption that battery packs currently cost approximately $650-700/kWh, and could fall to $150-200 at maturity. Declining capital cost parameters were estimated based on past studies using CIMS and to help align future cost projections[65]. Note that for E85 flex fuel vehicles, gasoline and E85 compete to meet fuel demand. For regular gasoline vehicles, the ethanol blended into gasoline is assumed to not exceed the levels required under the federal and provincial renewable fuel mandates (5 to 8.5%, depending on the province).

Intangible costs for vehicles are set to approximately align a baseline projection with no policies to historical trends and future projections. Since government statistical data and projections on vehicle sales in Canada weren't readily available, we used US-based data and projections from

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[63] It should be noted that while we here present all capital and intangible costs as single point values, these are represented in a model simulation by probability distributions that reflect information on their range, given real-world heterogeneity of capital costs and decision maker perceptions.

[64] National Research Council. (2013). *Transitions to Alternative Vehicles and Fuels*. Washington, DC: National Academy of Science. https://doi.org/10.17226/18264; Kromer, M. A., & Heywood, J. B. (2007). *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet*. Retrieved from http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/kromer_electric_powertrains.pdf

[65] For all motor technologies with declining capital costs, the rate parameter is 40 and the shape parameter is 0.006, as estimated by previous CIMS researchers.

the EIA's Annual Energy Outlook, as well as several non-academic sources, to approximate the Canadian market for calibration[66]. When setting intangible costs, we made judgemental assumptions on what portions of intangible costs were fixed costs (which includes factors such as convenience anxiety due to electric vehicles requiring lengthy periods of time for recharging) and what portion were non-fixed costs that decline over time with increased vehicle adoption (reducing the effect of unfamiliarity with electric vehicles or an initial dearth of public re-charging stations). Slightly different intangible costs for electric and plug-in hybrid vehicles were set in some provinces with low electricity rates to prevent unreasonably high market penetration of these vehicles in the *Reference Scenario*. Tables 8 and 9 show the capital and intangible costs for personal vehicle bodies and motors used in the model, and the resulting entire vehicle costs for a small car as an example.

Table 8: Personal Vehicle Body Capital and Intangible Costs and Motor Services Demand

Vehicle	Capital Cost ($2005)	Intangible Cost ($2005)	Motor Services Demand
Car - Small	16,200	15,000	0.62
Car - Large	25,000	-2,000	1.00
Truck - Small	28,400	5,000	1.52
Truck - Large	37,200	-14,000	0.81

Table 9: Personal Vehicle Motor Capital and Intangible Costs and Entire Car Costs

	Motor Capital Cost ($2005)		Motor Intangible Cost ($2005)		Capital Cost of Small Car ($2015)	
	2011-2015 period	*At Maturity*	*Initial*	*Lowest*	*2011-2015 period*	*At Maturity*
Gasoline - standard efficiency	5,000	5,000	0	0	22,400	22,400
Gasoline - high efficiency	6,000	6,000	0	0	23,100	23,100
Gasoline - hybrid	10,500	6,300	500	0	26,400	23,300
E85 Flex Fuel - high efficiency	6,250	6,250	2,750	500	23,300	23,300
E85 Flex Fuel - hybrid	10,700	6,400	2,250	500	26,500	23,400
Plug-in Hybrid	22,700	10,900	2,500 to 1,100	100 to 1,000	35,100	26,600
Electric	24,900	8,700	4,250 to 2,850	1,350 to 2750	36,700	25,100
Hydrogen	65,000	32,500	3,000	1,000	65,600	42,200

Note: In Tables 8 and 9, body and motor costs given in $2005 as entered in the model. Vehicle costs are given in $2015 assuming a 1.5% annual rate of inflation and motor service demand of 0.62 for a small car.

In the freight sector, truck capital costs represent the entire cost of the vehicle and are divided into trucks for light-medium (intra-city) transport and heavy (inter-city) transport. Capital costs were estimated based on previously existing values within CIMS and reports from the

[66] Desrosiers. (2015). Climate change and automotive sector. Retrieved from http://desrosiersblog.ca/?p=435; EIA. (2017). *Annual Energy Outlook 2017*. Retrieved from https://www.eia.gov/outlooks/aeo/tables_ref.cfm; Flavelle, D. (2015, June 19). Why hybrid car sales are stalling. *The Star*. Retrieved from https://www.thestar.com/business/2015/06/19/why-hybrid-car-sales-are-stalling.html; Klippenstein, M. (2016). Canadian Plug-in Electric Vehicle Sales. Retrieved from https://docs.google.com/spreadsheets/d/1dLFJwZVdvNLRpmZqPznlzz6PB9eHMe5b-bai_ddRsNg/edit#gid=25

International Council for Clean Transportation, the UC Davis Institute of Transportation Studies, and the MIT Centre for Transportation and Logistics[67]. The natural gas heavy freight truck represents an average of trucks running on liquefied natural gas and compressed natural gas. As with personal transport, we estimated declining capital cost parameters based on past studies using CIMS and alignment with future cost projections. We set intangible costs for diesel trucks to align with historical average fuel efficiencies as reported by Natural Resources Canada, while we estimated intangible costs for other types of trucks judgementally as a proportion of capital costs[68]. Table 10 shows the capital and intangible costs for freight vehicles used in the model. Note that for diesel trucks, regular diesel and drop-in renewable diesel compete to meet fuel demand, with conventional diesel always blended in at the levels required under the federal and provincial renewable fuel mandates (2% in most provinces). For biodiesel trucks, all fuel demand is met by conventional biodiesel.

Table 10: Freight Truck Capital and Intangible Costs

	Truck Capital Cost ($2005)		**Truck Intangible Cost ($2005)**	
	2011-2015 period	*At Maturity*	*Initial*	*Lowest*
Light-Medium			0	0
Diesel - standard efficiency	50,000	50,000	0	0
Diesel - medium efficiency	55,500	55,500	0	0
Diesel - high efficiency	62,300	62,300	0	0
Biodiesel - high efficiency	62,800	62,800	1,250	250
Plug-in Hybrid	94,500	72,700	10,000	2,500
Electric	125,100	75,700	20,000	5,000
Hydrogen	208,500	71,000	2,250	250
Heavy				
Diesel - standard efficiency	106,300	106,300	0	0
Diesel - medium efficiency	110,600	110,600	2,500	0
Diesel - high efficiency	121,900	121,900	5,000	0
Biodiesel - high efficiency	122,900	122,900	7,500	500
Natural gas	150,800	150,800	9,500	1,500
Hydrogen	411,000	181,500	12,000	2,000

[67] den Boer, E., Aarnik, S., Kleiner, F., & Pagenkopf, J. (2013). *Zero emissions trucks: An overview of state-of-the-art technologies and their potential*. Retrieved from http://www.theicct.org/sites/default/files/publications/CE_Delft_4841_Zero_emissions_trucks_Def.pdf; Fulton, L., & Miller, M. (2015). *Strategies for low-carbon emission trucks in the United States* (Sustainable Transportation Energy Pathways Program). Retrieved from http://steps.ucdavis.edu/files/06-11-2015-STEPS-NCST-Low-carbon-Trucks-in-US-06-10-2015.pdf; Jaffe, A. M., Dominguez-Faus, R., Lee, A., Medlock, K., Parker, N., Scheitrum, D., … Fan, Y. (2015). NextSTEPS White Paper: Exploring the Role of Natural Gas in U.S. Trucking, 1–69. Retrieved from http://steps.ucdavis.edu/files/02-18-2015-NextSTEPS-White-Paper-Natural-Gas-in-US-Trucking-18Feb2015-Public-Release.pdf; De Los Ríos, A., Goentzel, J., Nordstrom K. E. & Siegert, C.W. (2012). Economic analysis of vehicle-to-grid (V2G)-enabled fleets participating in the regulation service market. *IEEE PES Innovative Smart Grid Technologies (ISGT)*, Washington, DC, 2012, pp. 1-8. doi: 10.1109/ISGT.2012.6175658

[68] Natural Resources Canada. (2016). Comprehensive Energy Use Database. Retrieved from http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm

Mode Shift Parameters

In CIMS, mode shifting is determined by market share competitions between different modes of transport: in urban personal transport, this competition is between vehicle travel, public transit, and walking/cycling; and in heavy land freight transport, it is between trucks and rail. Since actual real-world mode shares do not resemble what would occur if decisions were based on financial costs alone, intangible cost parameters are used to represent real-world mode shifting. In personal vehicles, many people get extra value from using a car, be this due to convenience or status. In freight transport, trucks have several advantages over rail, notably the ability to deliver and pick up goods virtually anywhere.

Thus, for personal transport, we set intangible costs for mode shifting to result in approximately a 2 to 3% decrease in person kilometers traveled by vehicle for a 10% increase in gasoline prices, relative to what would have happened if fuel prices had stayed constant. This represents a -0.2 to -0.3 price elasticity of demand, which is a value cited in the empirical research literature[69]. Note that a one percent decrease in total vehicle kilometers traveled is not equivalent to a one percentage point decrease in vehicle kilometers traveled as a share of total person kilometers traveled. The percentage point reduction in market share for vehicle travel could be substantially smaller than the percent reduction in vehicle kilometers traveled, particularly if vehicle travel starts off as a high proportion of total vehicle kilometers traveled.

For heavy land freight transport, we set intangible costs to match historical shares of trucking and rail, as reported in the Natural Resources Canada Comprehensive End-Use Database[70]. The intangible costs result in varying price elasticities of demand in different periods, with the elasticity of tonne kilometers traveled by truck with respect to increases in diesel prices ranging from approximately -0.4 to -0.7. Again, note that a 1% change in tonne kilometers traveled is not equivalent to a one percentage point change in market share.

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[69] Goodwin, P., Dargay, J. & Hanly, M. (2004). Elasticities of road traffic and fuel consumption with respect to price and income: A review. *Transport Reviews*, 24(3): 275-292. http://dx.doi.org.proxy.lib.sfu.ca/10.1080/0144164042000181725; Fearnley, N et al. (2016). Triggers of urban passenger mode shift – state of the art and model evidence. Association of European Transport, 2016 European Transport Conference. https://abstracts.aetransport.org/paper/index/id/4792/confid/21

[70] Natural Resources Canada. (2017). Comprehensive Energy Use Database. Available at: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm

6. Modeling Results and Discussion

This section provides and discuss the results of our modeling exercise. Recall from Section 4 our scenarios and their assumptions as outlined in Table 11. The logic of choosing these scenarios emerges through the discussion of results below.

Table 11. Overview of Modeled Scenarios

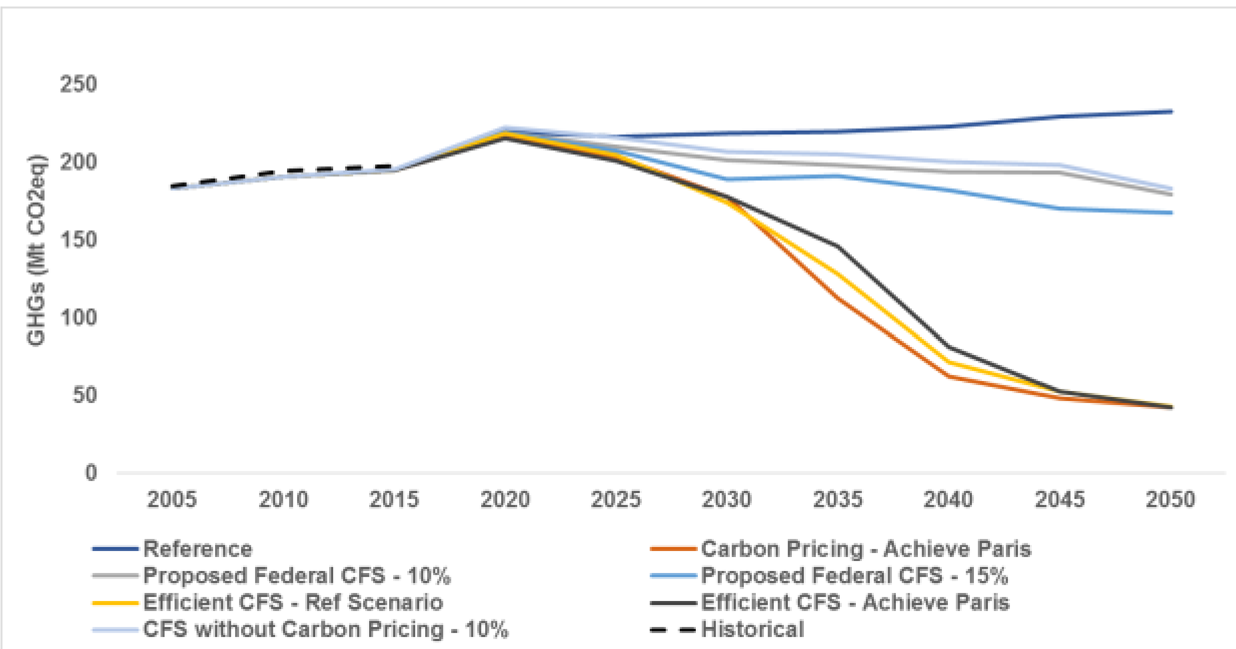
Scenario	Carbon Price Trajectory	National Transport Clean Fuel Standards
1. *Reference*	- All sectors: current federal backstop carbon price (rises to $50 by 2022 and remains at $50 thereafter)	No federal transport CFS
2. *Carbon Pricing – Achieve Paris*	- All sectors: carbon price trajectory so that Canada achieves 30% reduction by 2030 below 2005 levels (Paris target) and 65% reduction by 2050	No federal transport CFS
3a. *Proposed Federal CFS – 10%*	- All sectors: carbon price same as backstop in *Reference Scenario*	- 2030: 10% CFS emissions intensity reduction in transport relative to 2015 - 2050: 25% CFS emissions intensity reduction in transport relative to 2015
3b. *Proposed Federal CFS – 15%*	- All sectors: carbon price same as backstop in *Reference Scenario*	- 2030: 15% CFS emissions intensity reduction in transport relative to 2015 - 2050: 30% CFS emissions intensity reduction in transport relative to 2015
4a. *Efficient CFS – Ref Scenario*	- All sectors: carbon price same as backstop in *Reference Scenario*	2030 & 2050: CFS set to achieve same absolute reductions in transport as in *Carbon Pricing- Achieve Paris Scenario*
4b. *Efficient CFS – Achieve Paris*	- Transport: carbon price same as backstop in *Reference Scenario* - All other sectors: carbon price same as *Carbon Pricing Scenario* - Canada nationally achieves 30% reduction by 2030 below 2005 levels (Paris target) and 65% reduction by 2050	2030 & 2050: CFS set to achieve same absolute reductions in transport as in *Carbon Pricing- Achieve Paris Scenario*
5. *CFS without Carbon Pricing – 10%*	- All sectors: carbon price = 0 throughout Canada	- 2030: 10% emissions intensity reduction in transport relative to 2015 - 2050: 25% emissions intensity reduction in transport relative to 2015

6.1. Emissions Reductions and Carbon Intensities

This section focuses on results related to the transport emissions reductions and transport fuel carbon intensities for each scenario. Absolute emissions levels in the transport sectors for each scenario are shown in Figure 2. The average emissions intensities of transport fuels for each scenario are shown in Figure 3.

In the *Reference Scenario*, emissions in transportation increase from 2005 levels. Emissions are 18 and 26% above 2005 levels in 2030 and 2050 respectively (Figure 2, dark blue line). This increase is largely driven by increasing activity in freight. Emissions in personal transport, on the other hand, see a slight decline by 2030 but remain relatively constant thereafter. Meanwhile, the average emissions intensity of transport fuels sees a small decline of 4% below 2015 levels by 2030 and 9% by 2050 (Figure 3, dark blue bars).

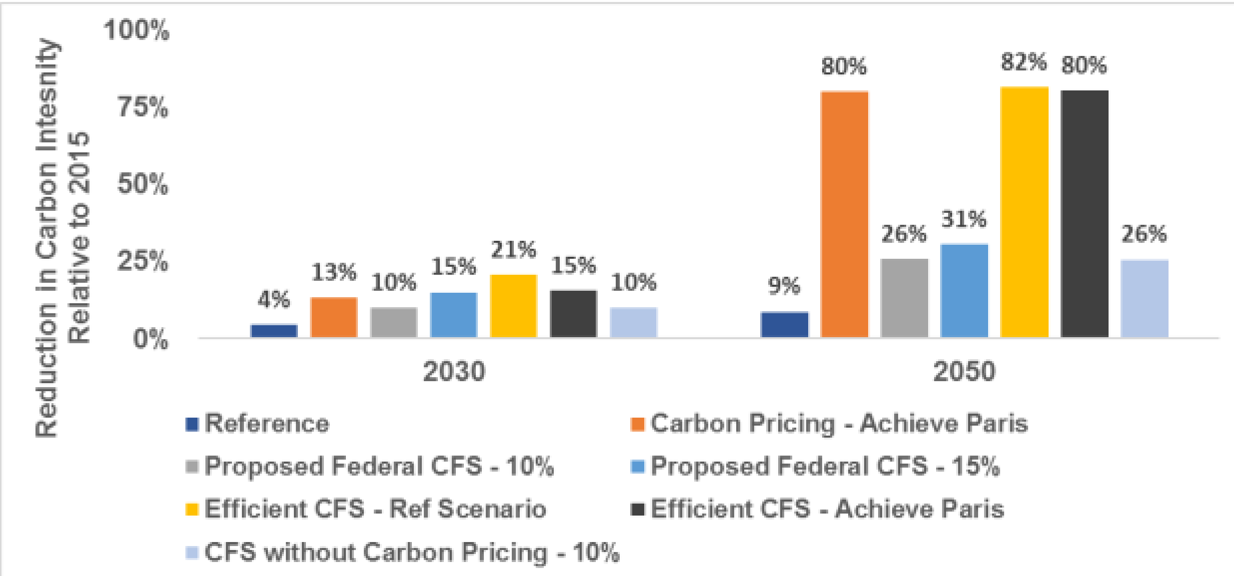
Figure 2: Emissions in Transport Sector in Each Scenario



Note: Emissions represented here include upstream emissions for biofuels and electricity production, but not upstream emissions for upstream oil and gas. Since oil and gas are imported and exported, we have not attempted to assess the impact of domestic transport policies on oil and gas upstream emissions in Canada. We use the simplifying assumption that biofuels consumed in Canada would be produced in Canada. To put transport emissions in context, Canada's total emissions were 749 Mt in 2005; a 30% reduction would equal 524 Mt and a 65% reduction 262 Mt.

The *Carbon Pricing – Achieve Paris Scenario* required a price starting at $15/tonne in 2018, rising by $15 per year to $195 by 2030, and then by $8 per year to $355 in 2050. Note that these values are all in 2017$, and thus the nominal carbon price applied in each year would need to be indexed to inflation. In this scenario, substantial emissions reductions occur in transport, particularly relative to the increasing emissions in the *Reference Scenario*. Transport emissions are reduced below 2005 levels by 4% in 2030 and 77% in 2050 (Figure 2, orange line). The average emissions intensity of transport fuels declines by 13% by 2030 and 80% by 2050 (Figure 3, orange bars).

Figure 3: Reduction in Average Carbon Intensity of Transport Fuels in 2030 and 2050 Relative to 2015 in Each Scenario



With an economy-wide carbon price that achieves the 2030 Paris target, transport emissions are 41 Mt below their level in the *Reference Scenario*. However, the federal government has noted that its proposed CFS would only achieve 30 Mt of emission reductions relative to current measures in place prior to the Pan-Canadian Framework, and those reductions would come from not just transport, but from all fuels used in transport, buildings and industry[71]. To achieve the Paris commitment, therefore, either the CFS must be much more stringent or the carbon pricing backstop must rise more rapidly by 2030, including in the near term to 2022. Alternatively, given that CFSs in other jurisdictions have been applied only to transport, the federal government could limit the application of the CFS to that sector while applying other policies in buildings and industry, such as tighter building codes and stringent industry emission performance standards. Finally, because the C*arbon Pricing Scenario* reduces transport emissions by 41 Mt below the *Reference Scenario*, we assume that this amount represents the economically efficient contribution from the transport sector to the achievement of Canada's 2030 Paris commitment.

In the *Proposed Federal CFS – 10% Scenario*, emissions in transport in 2030 are 17 Mt below the *Reference Scenario* (Figure 2, grey line), while in the *Proposed Federal CFS – 15% Scenario*, emissions in transport in 2030 are 30 Mt below (Figure 2, medium blue line). Thus,

[71] Recall that our *Reference Scenario* includes several measures from the Pan-Canadian Framework, include the federal backstop carbon price and coal-phase out, which means that our *Carbon Pricing-Achieve Paris Scenario* likely achieves even more than 41 Mt of incremental reductions in transport relative to the federal government's definition of current measures.

both scenarios achieve fewer emissions reductions in transport than the 41 Mt that would be required to efficiently meet the Paris commitment. Recall that these two scenarios assume no additional policies in other sectors.

By design, both *Efficient CFS Scenarios* achieve the same amount of transport emissions reductions in 2030 as in the *Carbon Pricing – Achieve Paris Scenario* – 41 Mt (Figure 2, black and yellow lines). But the intensity reduction depends on the stringency of policies in other sectors. If no additional policies are adopted in other sectors (*Efficient CFS – Ref Policy Scenario*), we find that the CFS emissions intensity reduction in 2030 would need to be 21% (Figure 3, first yellow bar), instead of the 10-15% contemplated by the government in its initial statement of CFS policy intention. If policies stringent enough to achieve the Paris target are adopted in all other sectors (*Efficient CFS – Achieve Paris Scenario),* the CFS intensity reduction would only need to be 15% (Figure 3, first black bar).

The main reason for the difference in CFS requirements is that stringent policy in other sectors to nationally achieve the Paris target leads to reduced growth in economic output and thus reduced growth in freight activity, such that total tonne-kilometers-travelled in freight is 8% lower in the *Efficient CFS – Achieve Paris Scenario* than the *Reference Scenario*. With lower freight transport, the same emission reductions can occur despite a higher emissions intensity per tonne-kilometer-travelled than in the *Efficient CFS – Ref Scenario*. After 2030, both versions of the *Efficient CFS Scenario* require rapidly declining emissions intensity, reaching an 80% intensity reduction by 2050 (Figure 3, second yellow and black bars).

When government is considering a package of climate policies, it is valuable to estimate the relative contribution of each to its objective. The federal government says it will layer its CFS on top of the backstop federal carbon price. To assess the contribution of the two policies, we re-ran the federal CFS with a 10% intensity reduction in 2030 and 26% reduction in 2050, but removed all carbon pricing from all provinces (*CFS without Carbon Pricing – 10% Scenario)*. (Note that provinces that had carbon pricing in place prior to the federal government's plans to implement a minimum national price would likely maintain their carbon prices in the absence of the federal minimum price, and thus this scenario is purely illustrative.)

The *CFS without Carbon Pricing – 10% Scenario* achieved 12 Mt of reductions in 2030 relative to the *Reference Scenario* (Figure 2, light blue line). Recall that when the CFS was layered on top of the minimum federal carbon price (*Proposed Federal CFS – 10% Scenario)*, 17 Mt of reduction were achieved in 2030 (Figure 2, grey line). Thus, adding the CFS and removing all carbon prices achieves approximately 70% of the reductions that would be achieved if the CFS was layered on top of carbon pricing. In 2050, the difference between the two scenarios is even smaller: a CFS with a 26% intensity achieves 50 Mt of reduction relative to the *Reference Scenario* if all carbon prices are removed, and 54 Mt if carbon pricing is maintained. Thus, the CFS policy alone by 2050 removes the need for a carbon pricing policy.

However, for a time, the CFS without carbon pricing achieves somewhat smaller reductions than the CFS with carbon pricing, because the carbon price leads to slightly higher fuel costs due to its taxing of all emissions. This leads to slightly more of the emission reducing actions that are supplemental to reductions in fuel carbon intensity – these being switching to more fuel-efficient vehicles, mode switching, and overall demand reduction. However, the effect of adding rising carbon pricing to the CFS is not substantial, and this difference becomes even smaller as the CFS drives carbon intensity toward zero and causes fuel price increases between 2030 and 2050.

It is also interesting to consider whether adding more policies to transportation, in addition to the CFS and carbon price, will achieve additional emission reductions. The federal government has announced that it plans to adopt a zero-emission vehicle (ZEV) strategy to increase the number of ZEVs on the road[72]. Such a strategy could potentially include a partial-zero emission vehicle (PZEV) mandate, which would require vehicle manufacturers to sell an increasing percent of zero and near-zero emission vehicles.

We chose not to model a PZEV mandate in our scenarios. The reason is that the emissions reductions from adopting a PZEV mandate and a stringent CFS will not be additive because the more stringent policy will determine emission reductions. Thus, if the CFS is more stringent, a PZEV mandate would contribute to achieving the CFS intensity reduction but would not lead to additional emission reductions. If the PZEV was more stringent, it may push the average carbon intensity of fuels below the CFS requirement, rendering the CFS non-binding. This is not to say that the two policies shouldn't be adopted together – they have the potential to complement one another, in that the PZEV would push vehicle manufacturers to increase production and availability of PZEV models, while the CFS would push fuel suppliers to increase the supply of the low carbon fuels that these vehicles would demand.

6.2. Comparing Carbon Pricing and a Clean Fuel Standard

In this section, we compare the *Carbon Pricing Scenario* to the *Efficient CFS – Achieve Paris Scenario* to assess the relative role of emission-reducing actions in transport of two different policy approaches – carbon pricing vs flexible regulations on fuels – that achieve approximately the same 2030 and 2050 emission reductions, both in transport and economy-wide. Recall that the following actions can reduce emissions in the transport sector: (1) fuel switching, (2) increased energy efficiency, (3) transport mode switching, and (4) reduced mobility demand for people and freight. We explore each of these in turn for people and freight transport to assess likely differences in economic efficiency between the two policy approaches. While we do not estimate the full welfare costs and benefits of the two approaches, our analysis of the ways in which they achieve the 2030 and 2050 commitments provides insights into their similarities and differences, including from an economic efficiency perspective. To provide context, we first show the effect of each policy on retail fuel prices.

Fuel Retail Prices

Retail fuel prices are the main driver of the emission-reducing actions in each scenario. The retail price of fuels includes their production costs, carbon charges and the net effect on production

[72] Government of Canada. (May 26, 2017). Government of Canada to develop a national Zero-Emissions Vehicle Strategy by 2018. News Release. Available at https://www.canada.ca/en/transport-canada/news/2017/05/government_of_canadatodevelopanationalzero-emissionsvehiclestrat.html

costs of buying or selling credits and debits in a CFS. Recall, however, that a carbon price taxes all fossil fuel-related carbon emissions of all fuels whereas a CFS causes cross-subsidization between fuels with carbon intensities above and below the CFS intensity requirement.

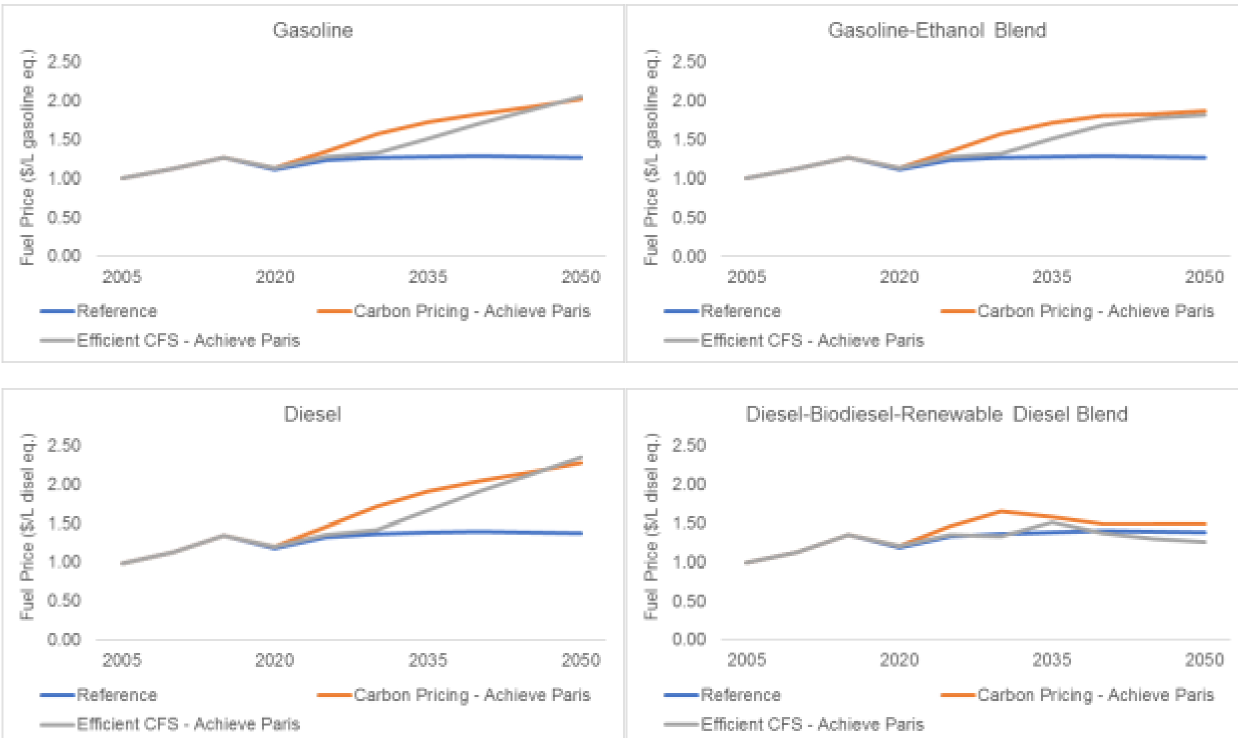
Figure 4 shows the retail prices of liquid fuel under *Reference*, *Carbon Pricing – Achieve Paris*, and *Efficient CFS – Achieve Paris*. At low to moderate levels of stringency, the carbon pricing approach leads to higher retail gasoline and diesel prices than under the flexible regulation (Figure 4, left-hand side), since the former is taxing all emissions while the latter is only requiring purchases of credits for a portion of the emissions. However, as the policies increase in stringency, the difference between the retail prices decreases. This means that the incentive to fuel switch, increase energy efficiency, mode switch, and reduce demand for mobility becomes increasingly similar between the two policies with increasing stringency. By 2050, retail prices of gasoline and diesel in the CFS scenario slightly surpass retail prices in the carbon pricing scenario. This occurs to compensate for somewhat fewer purchases of lower emission vehicles in earlier years with the CFS, when retail prices of gasoline and diesel were lower than under the carbon price.

The retail prices for the gasoline-ethanol blend follow a similar trajectory, with the difference in retail prices between the two scenarios becoming smaller with increasing policy stringency (Figure 4, top right). The retail price trajectories for the diesel-biodiesel-renewable diesel pool follows a somewhat different trajectory, with prices of the two scenarios getting closer, and then the prices in the CFS scenario falling below those under the carbon pricing scenario (Figure 4, bottom right). Recall that both policies achieve an overall carbon intensity reduction in freight of approximately 80%. While the impact of the two policies should be identical when a 100% carbon intensity reduction is achieved, there will still be some differences at prices prior to that point. As is shown in the following section, both scenarios fully phase-out conventional diesel use by 2050. Thus, in the final decade, the retail price in the diesel-biodiesel-renewable diesel pool is based only on the prices of biodiesel and renewable diesel. Because the production costs of these renewable fuels fall slightly with greater production, retail prices also fall.

The price does, however, fall more in the CFS scenario than in the carbon pricing scenario. With the carbon price, the small amount of upstream emissions in the production of biodiesel and renewable diesel in 2050 are still being taxed. With the CFS, however, the carbon intensity of biodiesel and renewable diesel are still below the required carbon intensity, so they are still subsidized through the sale of CFS permits. Although there are no subsidies coming from the sale of conventional diesel, which has fallen to zero, gasoline is still being sold and it is in the common pool of fuels under the CFS. This means that retailers of gasoline are still purchasing credits and therefore still providing a cross-subsidy that lowers the prices of the diesel-biodiesel-renewable diesel blend (Figure 4, bottom right).

This dynamic with diesel prices does not occur in the gasoline-ethanol blend since gasoline is still consumed in 2050 in both scenarios (Figure 4, top right). Ethanol only makes up approximately 40% of the gasoline-ethanol pool in both scenarios in 2050, with much of the emission reductions having been achieved in personal transport via switching to electric vehicles.

Figure 4: Canadian Average Retail Prices of Fuels under *Reference*, *Carbon Pricing – Achieve Paris*, and *Efficient CFS – Achieve Paris* Scenarios



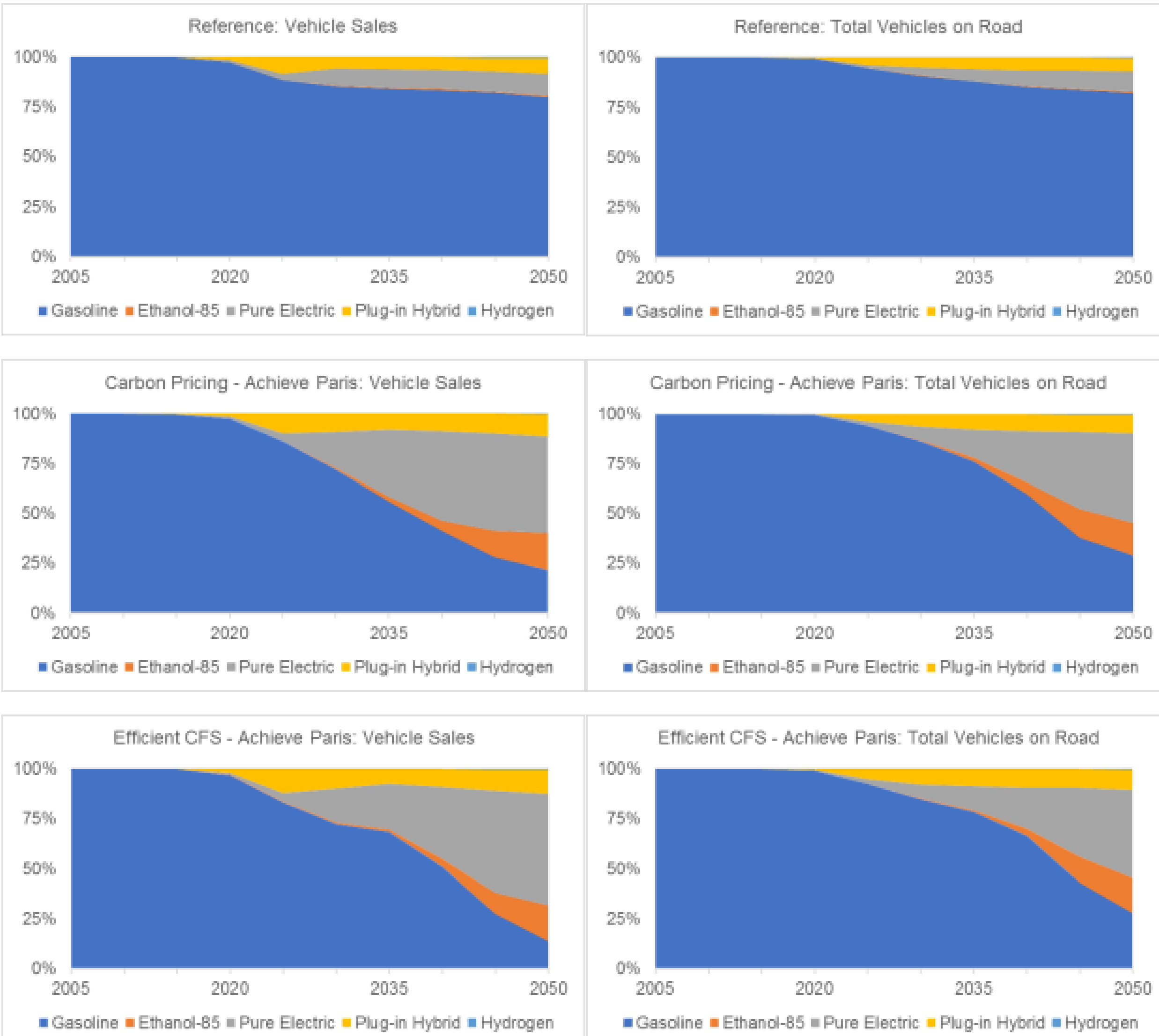
Note: Prices for the fuel blends are weighted by actual consumption of each of the fuels in the blend.

1) Fuel Switching

In personal transport, the *Reference Scenario* sees little fuel switching, with gasoline vehicles still accounting for approximately 80% of the vehicle stock in 2050. In contrast, the carbon pricing and flexible regulation scenarios see substantial fuel switching. In both scenarios, the proportion of gasoline vehicles on the road falls from close to 100% currently to approximately 85% by 2030 and approximately 30% by 2050. Figure 5 displays the percent of sales and total vehicles on the road for each fuel over time for the three scenarios.

The trajectories for uptake of alternative fuel vehicles follow relatively similar paths in the two scenarios. Based on the financial and behavioural parameters in our model, pure electric vehicles account for the largest proportion of alternative fuel market share, followed by plug-in hybrids and flex fuel vehicles that consume ethanol-85. The exact percent of each vehicle type varies only slightly in most years between the two scenarios, with the CFS scenario having 1% more alternative fuel vehicles on the road than the carbon pricing scenario in both 2030 and 2050. This similarity suggests that carbon pricing and the CFS provide almost identical incentives for fuel switching in personal transport.

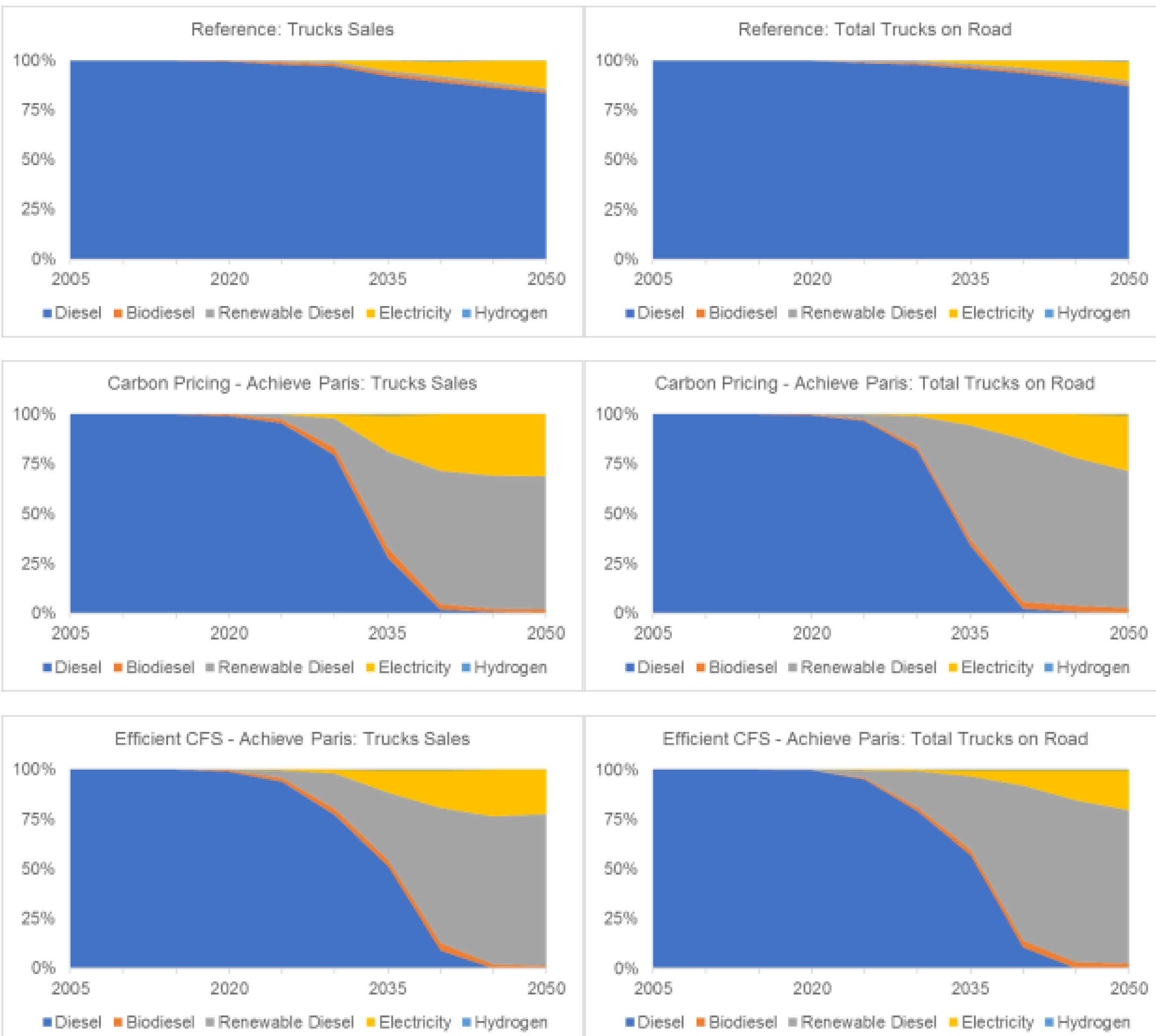
Figure 5: Personal Transport Vehicle Sales and Total Vehicles on Road in *Reference*, *Carbon Pricing – Achieve Paris*, and *Efficient CFS – Achieve Paris* Scenarios



In freight transport, the *Reference Scenario* similarly sees limited fuel switching, with diesel accounting for approximately 85% of fuel in light-medium freight and approximately 95% of fuel in heavy freight in 2050. Meanwhile, the two scenarios that achieve Paris see substantial fuel switching, with alternative fuels completely replacing diesel by 2050. Figures 6 and 7 display the percent of sales and total trucks on the road for each fuel over time for the three scenarios for light-medium and heavy freight.

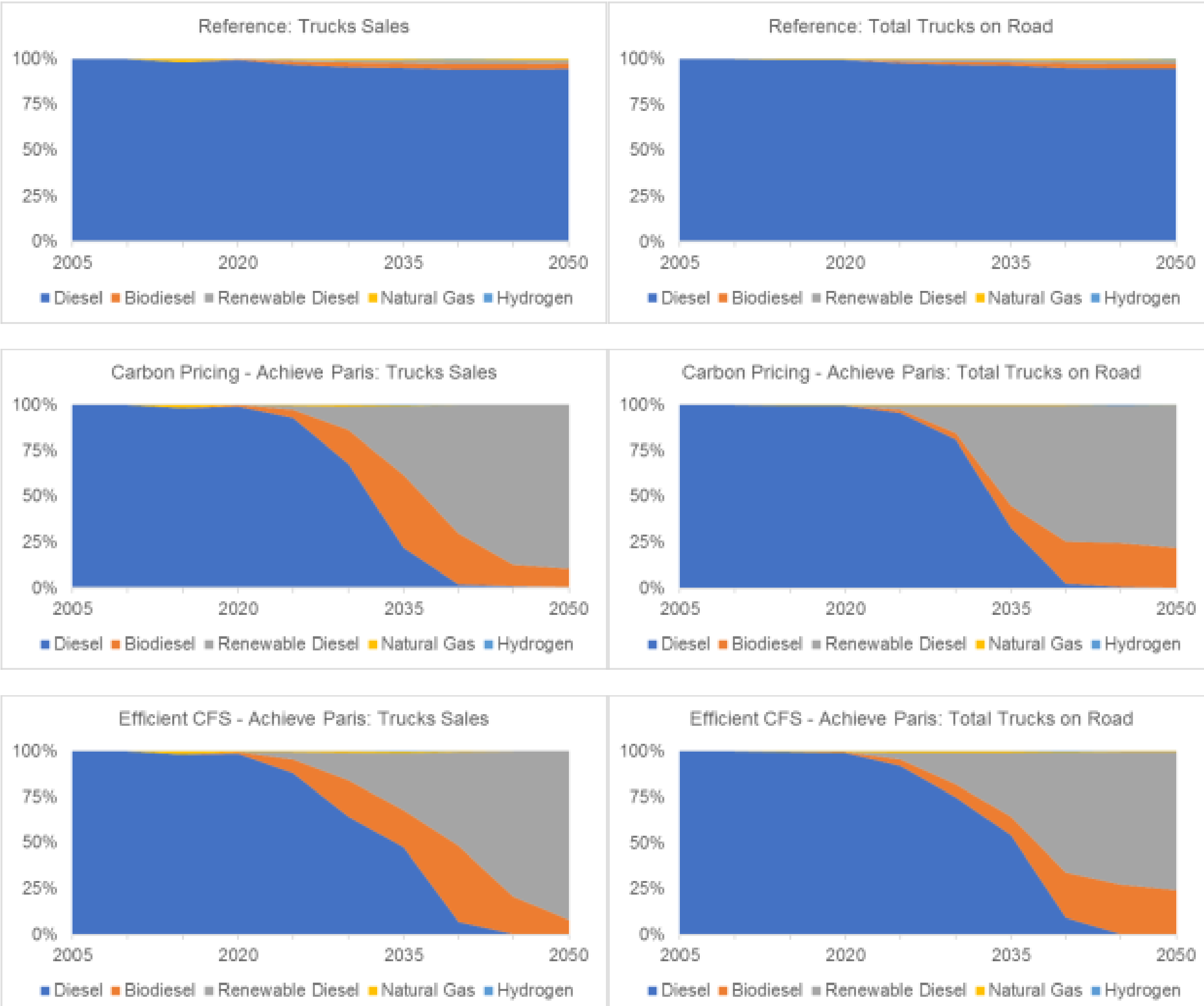
As with personal transport, both scenarios lead to similar choices of alternative fuels. In both light-medium and heavy freight, drop-in renewable diesel (which may take forms such as hydrogenation-derived renewable diesel (HDRD) and biomass-to-liquids) accounts for most alternative fuels. In light-medium freight, electricity also plays a role, while in heavy freight conventional biodiesel plays a role. There are small differences. The CFS results in 3% less market share for diesel in light-medium freight and 6% less in heavy freight in 2030. The CFS also results in slightly less uptake of electric trucks (8% lower total market share in 2050) and a slightly greater role for biofuels in light-medium freight. The reason is that the carbon price, by taxing all emissions, leads to slightly higher fuel costs for trucks running on diesel-renewable diesel blends, which makes for a smaller cost difference between the diesel trucks and electric trucks.

Figure 6: Light-Medium Freight Truck Sales and Total Trucks on Road in *Reference*, *Carbon Pricing – Achieve Paris*, and *Efficient CFS – Achieve Paris* Scenarios



Note: Biodiesel refers to conventional biodiesel. Renewable diesel refers to drop-in renewable diesel such as hydrogenation-derived renewable diesel and biomass-to-liquids renewable diesel.

Figure 7: Heavy Freight Truck Sales and Total Trucks on Road in *Reference*, *Carbon Pricing – Achieve Paris*, and *Efficient CFS – Achieve Paris* Scenarios



Note: Biodiesel refers to conventional biodiesel. Renewable diesel refers to drop-in renewable diesel such as hydrogenation-derived renewable diesel and biomass-to-liquids renewable diesel.

2) Increased Energy Efficiency

The fuel efficiency of vehicles is impacted by several factors, including vehicle size, type, and the energy efficiency of the motor. In the two scenarios that achieve the Paris commitment, improved fuel efficiency plays a relatively small role in achieving emissions reductions above the *Reference Scenario*. One reason is that existing federal vehicle fuel efficiency standards are already substantially increasing vehicle efficiency in the *Reference Scenario*. Additionally, behavioural evidence, as reflected by key parameters in our model, acknowledge that even if these are costly to operate, a significant share of vehicle users will continue to choose large, power-hungry vehicles for reasons of perceived need, status and other non-financial considerations.

Figure 8 shows the percent sales of personal vehicles by type and size in each scenario. The vehicle size categories are broad approximations. Note that in CIMS, the efficiency of a personal vehicle is determined by a combination of the size of the vehicle purchased and the efficiency of motor, with several levels of motor efficiency available for internal combustion engine vehicles; here we compare vehicle sizes but not motor efficiencies. In 2030, the carbon pricing scenario sees somewhat more switching away from large cars and trucks than the CFS scenario. This is because the carbon price taxes all emissions and thus leads to higher fuel prices. By 2050, the carbon price and CFS lead to nearly the same percent of vehicle sales from each type and size category. As both policies move towards deep emission reductions, they provide similar, albeit weak, incentives to shift towards smaller vehicles. Nonetheless, the similar results under carbon pricing and the CFS in 2050 point towards similarities in economic efficiency between the two policies when the policy stringencies are both high.

Figure 8: Personal Vehicle Sales by Vehicle Type and Size in 2030 and 2050 in *Reference*, *Carbon Pricing – Achieve Paris*, and *Efficient CFS – Achieve Paris* Scenarios

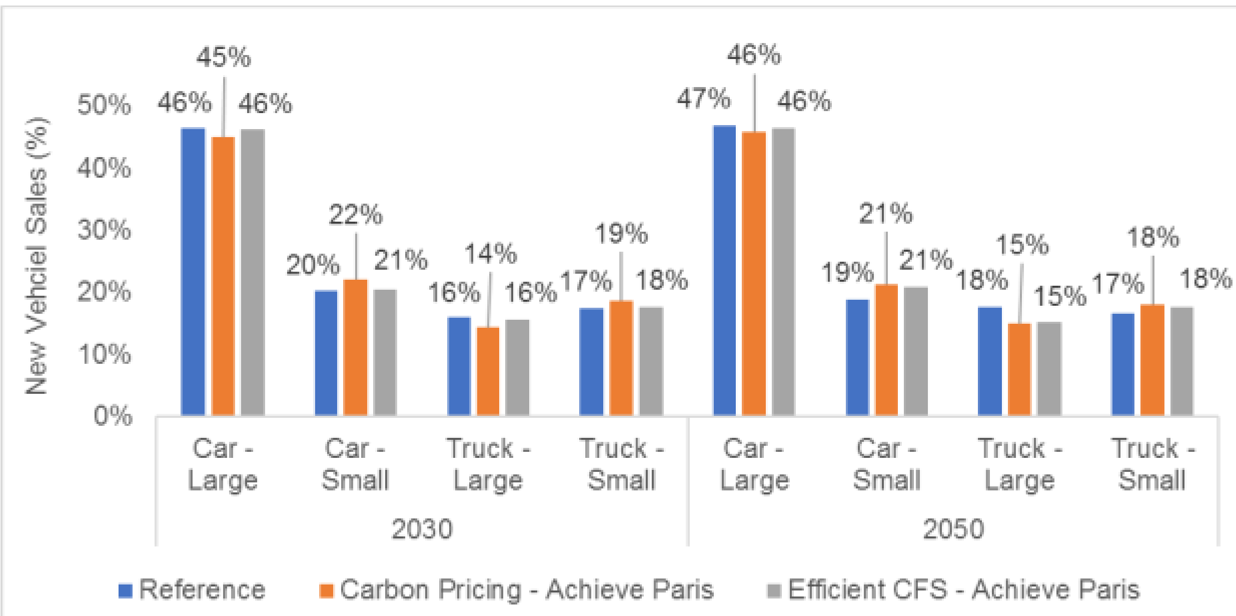
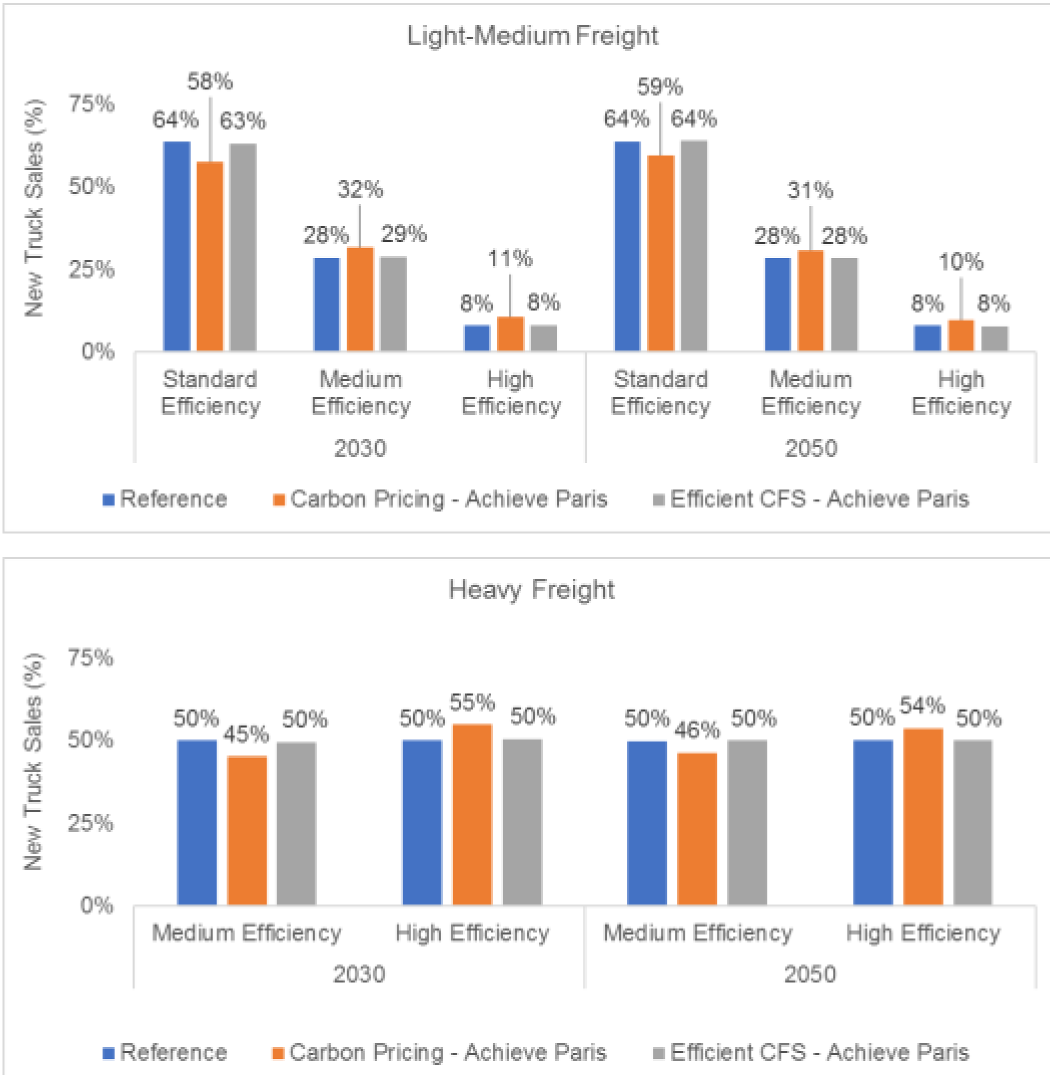


Figure 9 shows percent sales of freight trucks by fuel efficiency in each scenario. In both 2030 and 2050, the carbon pricing scenario sees more purchases of trucks with higher fuel efficiency than the CFS scenario. Recall that the fuel retail prices for the diesel-biodiesel-renewable diesel pool in the CFS scenario are below those under carbon pricing. While fuel efficiency improvements for trucks play a relatively small role in our simulations, the incentive to switch to fuel-efficient vehicles is larger under carbon pricing, thus pointing to a modest source of economic inefficiency in the CFS relative to carbon pricing.

Figure 9: Freight Truck Sales by Fuel Efficiency in 2030 and 2050 in *Reference, Carbon Pricing – Achieve Paris*, and *Efficient CFS – Achieve Paris* Scenarios

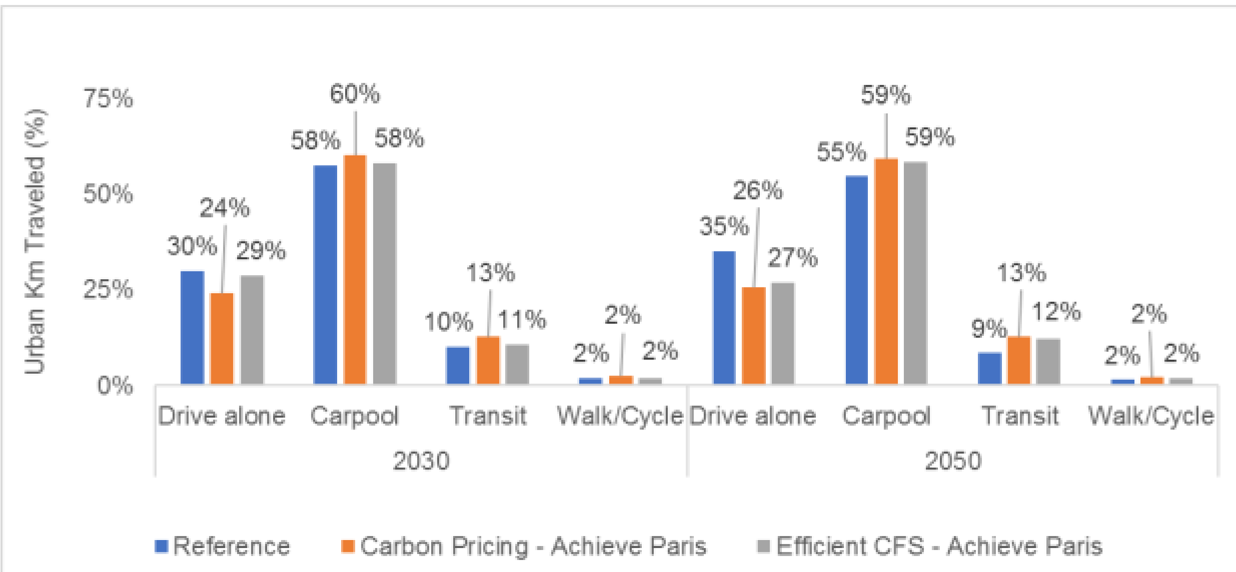


3) Transport Mode Switching

In personal transport, our results show mode switching making a relatively small contribution to achieving emission reductions in both scenarios. Despite increases in fuel costs, many people will continue to drive vehicles due to preference, convenience and status. It also should be kept in mind that the increases in the proportion of trips by foot and bicycle may not lead in many cases to an equivalent increase in the proportion of distance traveled by these means, since it is more likely that switching to these forms of active transportation would occur for shorter rather than longer trips. Finally, there is a feedback effect to consider. As some people shift to non-vehicle modes of travel, road congestion declines, and this increases the attractiveness of vehicles. Urban transport experts note that even in cities with high vehicle costs high fuel prices, and high parking charges, in addition to excellent alternative services from transit, bike and walking networks, urban arterial roads nonetheless exhibit intensive vehicle use.

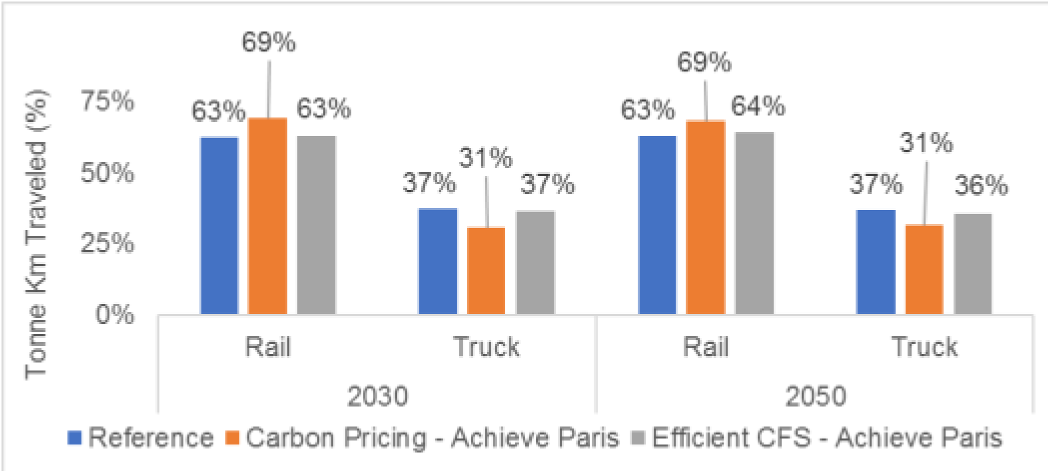
In 2030, the carbon pricing scenario sees a slightly larger shift away from single-occupancy vehicles towards carpooling and transit, in comparison to the CFS scenario (Figure 10). In 2050, however, the proportions of each mode for urban transport are similar in the two scenarios. As with vehicle energy efficiency, the fact that a carbon price taxes all emissions leads to a somewhat larger incentive to shift modes at lower policy stringencies. However, as the stringency of both policies increase, the difference in fuel prices shrinks and the incentive to shift mode approaches equivalency. Thus, again it appears that the carbon price and CFS may not have large difference in economic efficiency for personal transport.

Figure 10: Urban Personal Transport by Mode in 2030 and 2050 in *Reference*, *Carbon Pricing – Achieve Paris*, and *Efficient CFS – Achieve Paris* Scenarios



Heavy freight goods can be transported on land by rail or truck, with rail being more fuel efficient, and thus more economically efficient for point-to-point transport of high-weight raw materials and manufactured goods, but trucks offering far more convenience in terms of deliveries to a diversity of point destinations. As with truck fuel efficiency improvements, more shipping by rail occurs in the carbon pricing scenario (Figure 11). This is caused by that scenario's higher fuel prices, and again indicates a modest relative economic inefficiency with the CFS. However, switching from trucks to rail plays a relatively small role in achieving emission reductions even in the carbon pricing scenario because of the advantages of trucks.

Figure 11: Heavy Freight by Mode in 2030 and 2050 in *Reference*, *Carbon Pricing – Achieve Paris*, and *Efficient CFS – Achieve Paris* Scenarios



4) Reduced Mobility Demand for People and Freight

Based on the assumptions in our model, demand reduction plays a negligible role in reducing emission in personal transport. In the both scenarios, total personal kilometers travelled is within 2% of the *Reference Scenario* in all periods of the simulation. Again, our model's parameters reflect evidence of human mobility preferences, especially since gradually rising incomes would somewhat offset the small increase in mobility costs due to climate policy. Moreover, if that climate policy leads to substantial uptake of plug-in electric vehicles and widespread availability of fast charging infrastructure, the long-term outcome could be lower vehicle mobility costs because of the much higher energy efficiency of electric motors. Thus, there is a possibility that climate policy could lead to increases in total distances traveled using vehicles in Canada.

With freight transport, however, demand reduction plays a role in reducing emissions. In both scenarios, demand for freight decreases by 8% in 2030 and 10% in 2050, relative to the *Reference Scenario*. In our model, changes in demand for freight are driven by changes in output in the industrial sector, since slower growth in the production and consumption of goods would require slower growth in freight transport. Since we assume that the stringency of policies outside of the transport sector is the same in both scenarios, the impact on demand for freight is the likewise the same.

6.3. Contribution of Biofuels

Biofuels play a role in reducing transport emissions, particularly in freight, in our scenarios that achieve the Paris 2030 commitment and the 65% reduction in 2050. Total annual biofuel consumption in 2050 for transport and for low-emission production of the biofuels consumed in transport is 2,086 PJ in the carbon pricing scenario and 2,233 PJ in the CFS scenario, as shown in Table 12. Recall from Section 2 that the Global Energy Assessment (GEA) order of magnitude estimate for sustainable biofuel production in Canada in 2050 is 1,700 to 2,200 PJ if all available sustainably produced feedstock (except for animal waste) were used for transport, and none for electricity and heat production. While our scenarios result in consumption in transport near the upper end of this estimate, we emphasize that the GEA states that its estimates are *order of magnitude* values, consisting of an average of low and high estimates. We compare the amount of biofuels used in our scenarios to GEA as a comparison against one estimate of sustainable biomass availability from a reputable, leading research institute. However, as noted in Section 2, there are many different estimates of sustainable biofuel potential in the literature that vary widely. It is beyond the scope of this study to conduct a full review and assessment of all these estimates. But if biomass availability becomes an issue, this simply means that low-emission alternatives, such as electricity and perhaps hydrogen, will gain somewhat larger market shares than we show in our simulations. The declining market share of gasoline and diesel will be about the same, as this reduction is necessary to achieve the 2030 and 2050 emission commitments. Our simulations are intended to be approximately indicative rather than precisely predictive.

Table 12: Consumption of Biofuels in Transport and for Biofuel Production in *Carbon Pricing – Achieve Paris* and *Efficient CFS – Achieve Paris* Scenarios

	Biofuel Consumption in Modeled Scenarios (PJ)				**GEA Estimate of Sustainable Biofuel Production in Canada in 2050 (PJ)**
	2030		***2050***		
	Carbon Pricing - Achieve Paris	*Efficient CFS - Achieve Paris*	*Carbon Pricing - Achieve Paris*	*Efficient CFS - Achieve Paris*	
Personal	50	50	218	231	
Freight	384	452	1,762	1,895	
Biofuel Production	21	29	118	127	
Total	**455**	**531**	**2,098**	**2,253**	**1,700 to 2,200**

Note: The estimate of sustainable biofuel production in Canada is from the Global Energy Assessment[73] and assumes that all available biomass is converted into biofuels for transportation, with none used for electricity or heat production. The row Biofuel Production indicates biofuels consumed in the production of biofuels to be used in transport; biofuels can be used in various stages of biofuel production, including farming, forestry, biofuel transport and biofuel production plants.

Estimating if a given amount of biofuel consumption in transport is sustainable is complex for several reasons. First, estimates of sustainable biofuel production potential, such as in the Global Energy Assessment (GEA), are highly uncertain. Second, the amount of sustainable biofuel *consumption* in Canada need not equal sustainable biofuel *production* in Canada. Imports of some sustainably produced biofuels might be possible. Third, the sustainable biofuel potential could be increased through technological developments in biofuel production and processing.

Furthermore, the amount of biomass available to produce transportation fuels will partially depend on the amount of biomass being used in other sectors. In our scenarios that achieve the 2030 and 2050 targets, biomass is also used in sectors outside of transportation, including for electricity generation and for heat production in industry. Thus, it is unlikely that all available biomass feedstock that is sustainability produced in Canada can be used in transport. Still, given

[73] GEA (2012). Global Energy Assessment - Toward a Sustainable Future. Chapter 11 – Renewable Energy. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

that the GEA value is an order of magnitude estimate, the total amount of biomass used in all sectors in our scenarios is reasonably close to what the GEA estimates can be sustainability produced in Canada. It is possible that competition for sustainable biomass supplies from other sectors could cause transport biofuel costs to rise to some degree, which we did not model.

All things considered, it is difficult to say with certainty if the amount of biofuel use in our simulation is sustainable. What note, however, that our estimated consumption is close in magnitude to the estimate of sustainable production from the GEA. Considering the uncertainties involved in our estimates and those of the GEA, particularly given that the projections for 2050 are over 30 years into the future, our results suggest that biofuels can sustainably make a substantial contribution to GHG emissions reductions in transport to mid-century.

6.4. Efficiency of Carbon Pricing and Flexible Fuel Regulations

In this section, we return to discussion of the economic efficiency difference between carbon pricing and flexible regulations in light of our results. Recall from Section 2 that some studies have found regulations to be a much costlier way to reduce emissions in transport than carbon pricing. We discussed several potential contributors to the findings that regulations are higher costs:

1. Assuming that biofuels have fixed, high lifecycle emissions.
2. Assuming that significantly reducing vehicle-based mobility has low welfare costs.
3. Limiting the comparison to policies with weak stringency.
4. Testing regulations with limited flexibility.
5. Comparing transport regulations to a carbon price that achieves a different amount of emissions reductions in transport.
6. Assuming high social and environmental impacts of biofuel production.

In our simulations, we ran both a carbon price and a CFS with modifications to the above assumptions, as follows:

1. We enabled biofuel production to make a cost-minimizing shift from higher to lower-emission production pathways in response to policy.
2. We included empirically estimated parameters of welfare costs (sometimes called intangible costs in the literature) from reduced vehicle-based mobility.
3. We compared policies when achieving deep emissions reductions in transport.
4. We designed a CFS with maximize flexibility by including all transport forms of energy and almost all transportation modes.
5. We compared the CFS to a carbon price that achieves the same amount of emissions reductions in the transport sector.

6. We assume limited social and environmental impacts of biofuel production because biofuel consumption in our simulation is within the range of estimates of sustainable biofuel production in Canada.

While we did not calculate explicit policy welfare costs in this study, we looked at retail fuel prices and market share results as proxies for relative economic efficiency when comparing policies. As shown in Section 6.2, there are many similarities in the retail fuel prices and market shares in our two scenarios that achieve the 2030 and 2050 commitments.

We detected, however, modest differences between the two policy approaches, and this suggests that their economic efficiency performances, while similar, are not identical. In the case of freight transport, in particular, there are differences throughout the simulation of up to 25% in retail fuel prices between the two policies, which causes differences in the incentive to improve truck fuel efficiencies and the incentive to mode shift from truck to rail. While this may suggest economic inefficiency in the CFS, it could be largely due to the particular design that we modeled interacting with our model parameters. Notably, we combined the gasoline and diesel fuel pools under one CFS reduction requirement. Based on the model parameters we used, diesel was completely eliminated by 2050 with the CFS, while some gasoline remained in use through to 2050. This led to the dynamic where the retail prices for the diesel-biodiesel-renewable diesel was significantly lower with the CFS than with carbon pricing, since use of gasoline was subsidizing use of biodiesel and renewable diesel. Separating the two pools under separate CFS reduction requirements may reduce this type of effect, but would also present the challenge of trying to judge the most economically efficient intensity reductions for each pool. Slightly different model parameters may have led to a more gradual reduction in diesel, so that diesel was not completely eliminated by 2050, and that could have also reduced this effect.

Overall, however, outcomes with the two policy approaches are closely matched. For both approaches, most emission reductions occur due to fuel switching. This differs from some studies where a large portion of reductions result from mode shift and demand reduction with carbon pricing, but not with regulations. In our study, since we assume that both electricity and biofuels can shift to relatively low emission production methods with the right policy incentives, and that mode shift and demand reduction often have substantial welfare costs that reduce their contribution to GHG reduction, fuel switching ends up being one of the lower cost ways to reduce emissions under carbon pricing. In turn, the amount of fuel switching under carbon pricing ends up being comparable to that which occurs with the CFS.

Furthermore, we note that retail fuel prices and fuel market shares, save a few exceptions, tend to become even more similar under the two policy approaches as the policies increase in stringency. This suggests that while other studies have found large cost differences when exploring regulations and carbon pricing at low stringencies, any cost differences will become much smaller at higher stringencies.

By designing the CFS to maximize flexibility – including all transport forms of energy and transport modes under one standard – our flexible regulation approximates the broad coverage and flexibility of a carbon price. An advantage of this broad coverage is that if one abatement option, such as the biomass-to-liquids diesel pathway or hydrogen fuel cell vehicles, remains a high cost option, other lower cost options can flourish under either the CFS or the carbon price. This in-built flexibility prevents a regulation like a CFS from forcing a high cost abatement option that carbon pricing would have enabled market participants to avoid.

Any modeling exercise has uncertainties, and thus it is possible that some of our assumptions may be overly optimistic or pessimistic. For example, it is possible that we are overly optimistic about the amount of biofuels that can be sustainability produced or overly pessimistic about people's willingness to switch from vehicles to other modes of transport. We do not claim that our assumptions are definitive. However, what our simulation shows is that when using assumptions that reflect current real-world behavior and market dynamics, flexible regulations may come much closer to the economic efficiency of carbon pricing than has been suggested in more restrictive studies.

7. Conclusion

7.1. Summary of Key Findings

This study has assessed several issues of relevance to applying a national CFS in Canada to rapidly reduce carbon emissions in transport. We examined evidence from the literature and real-world biofuel production data to assess the potential role for biofuels in decarbonizing transport. The evidence suggests that biofuels can be produced in ways that have low lifecycle emissions. The evidence also suggests that a substantial amount of biofuels can be produced without having major negative impacts on ecosystems and food production in Canada, although uncertainties exist with regards to exactly how much biofuels can be produced sustainably. We also reviewed studies that suggest regulations are far costlier than carbon pricing for reducing transport emissions, finding that a narrow set of restrictive assumptions contributed to these conclusions.

We then conducted our own energy-economy simulation modeling exercise in which we used different assumptions from those of the studies mentioned above to explore the use of either carbon pricing or a national CFS, both being very flexible policies, to reduce Canada's transport emissions. The results of our modeling exercise should be considered in light of the uncertainties we have identified. With that in mind, key results of our simulations include the following:

1. If applied across the country, the federal government's currently proposed minimum national carbon price will be insufficient to achieve substantial emission reductions in transport. Indeed, without additional policies, emissions may rise through to 2050.
2. A national CFS with an average fuel intensity reduction of 10% by 2030 would be insufficient to achieve the amount of transport emission reductions necessary for Canada to meet its 2030 Paris commitment in an economically efficient manner.
3. The emissions intensity reduction required for a CFS to achieve an economically efficient amount of reductions in transport is dependent on the stringency of policies applied in other sectors. In particular, growth in freight transport depends on the growth rate of Canada's industrial sectors and total economic output. If few additional policies

are applied in other sectors, the intensity reduction for a CFS policy would be approximately 20% by 2030. If, however, more stringent policies are applied in other sectors, a lower intensity reduction of 15% in transport would be sufficient.

4. In the period from 2030 to 2050, rapidly rising stringency of the policies would be required to continue decarbonizing transport. If Canada is to achieve economy-wide reductions of 65% by 2050, with a growing economy over the same decades, the carbon intensity of transportation fuels would need to fall by approximately 80%.
5. Our results show many similarities in retail fuel prices and market share outcomes when using either a carbon price or a CFS to achieve the same emissions reductions in transport. And these similarities increase with increasing policy stringency. Our findings suggest that the relative economic efficiency of carbon pricing and regulations is highly dependent on modeling assumptions. If we assume, as technological and economic data show, that production emissions of both biofuels and electricity can fall to low levels, that the CFS is designed to maximize flexibility by covering all transport fuels, and that dramatic mode shifting of people and freight is unlikely at estimated mobility costs, then the economic efficiency difference between carbon pricing and a CFS is small.

7.2. Study Limitations and Directions for Future Research

Like all research, this study has limitations from which we draw suggestions for future research. First, we limited the scope of our study to the application of a CFS in the transport sector. Yet the federal government is proposing a CFS that would cover transport, buildings, and industry. Future research could explore the application of a CFS in all these sectors.

Second, as discussed, we used a hybrid energy-economy model due to its suitability for representing technology-specific regulations. However, foregoing the separate or combined use with a computable general equilibrium model means that we do not try to directly measure the full macro-economic and welfare impacts of different policies. Thus, we do not calculate policy costs, but instead use market share and fuel price outcomes as proxies for assessing the relative economic efficiency of policies. In future research, we intend to address this issue.

Third, we did not conduct a formal uncertainty analysis that tested the effect of changes to key parameters and assumptions. Key uncertainties in our study include: future global oil prices, since higher prices for gasoline and diesel would likely encourage more shifting away from fossil fuels in transport, while lower prices would have the opposite effect; prices for biofuels, electricity, and hydrogen, since lower or higher prices could impact the degree of fuel switching in transport; and lifecycle emissions of biofuels, especially land-use emissions, since different assumptions could impact the emission reduction potential of biofuels. In future research, we intend to conduct uncertainty analysis on these and other parameters.

Fourth, we limited our treatment of biofuels to five key pathways and used assumptions of biofuel availability from other studies. A more in-depth analysis of biofuel potential in Canada could look at a broader range of biofuel pathways and tie availability more directly to land and feedstock availability.