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An evaluation of policy options for reducing greenhouse gas emissions in the transport sector: The cost-effectiveness of regulations versus emissions pricing

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An evaluation of policy options for reducing greenhouse gas emissions in the transport sector: The cost-effectiveness of regulations versus emissions pricing

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Abstract

The reduction of greenhouse gas emissions from road transport is a key policy goal that is being pursued by both federal and provincial governments using a range of policies. This paper considers the cost of alternative approaches to reducing emissions from road passenger travel in Canada. Our findings reinforce the widely-held belief that a revenue-neutral carbon tax is the most cost-effective tool to reduce greenhouse gas emissions. Regulatory instruments on their own, such as a low carbon fuel standard, vehicle greenhouse gas intensity regulation, or zero emission vehicle mandate, achieve a given reduction at much higher cost. We show, however, that a combination of regulatory instruments can better approach the cost-effectiveness of a carbon tax than individual regulations. We provide insight about the optimal combination of regulatory instruments in the Canadian context, and find that both a low carbon fuel standard

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and an zero emission vehicle mandate can be jointly used to reduce GHG emissions from the transport sector. Our analysis is timely, given the rapidly evolving policies in this sector.

Keywords: Greenhouse gas emissions, low carbon fuel standard, electric vehicles, carbon tax, road transport

1 Introduction

Passenger on-road transport emissions, primarily associated with driving cars and light trucks, make up a significant share of all greenhouse gas emissions in Canada. The transport sector is also one of the most visible sources of emissions, since most Canadians travel by vehicle on a regular basis. Moreover, in addition to producing greenhouse gas emissions, private vehicles generate a number of other social costs, including accidents, congestion, and local air pollution. As a result, provincial and federal governments in Canada have targeted passenger vehicles with a large number of different types of policies. For example, governments have used fuel economy standards and greenhouse gas intensity standards for new vehicles, gasoline taxes, taxes and subsidies on new vehicles, support for public transit, and other policies aimed at reducing emissions from the passenger transport sector. Under the newly negotiated *Pan-Canadian Framework on Climate Change*, several new policies are likely to be added to this list. Three are particularly prominent: a carbon price, to be imposed by provinces and backstopped by the federal government; a clean fuel standard; and an electric vehicle strategy.[1]

In this paper, we analyze the cost-effectiveness of these policies aimed at reducing greenhouse gas emissions from the transport sector. We do so by developing a simple and transparent economic model. The model is a general equilibrium model focusing on the transport sector. It shares similarities with other transport sector economic models, for example by (Anderson et al., 2016; Vass and Jaccard, 2017; Fischer et al., 2007; Fullerton and West, 2002, and others). We calibrate the model with parameters that are representative of the Canadian transport sector and use it to simulate a large number of policies aimed at reducing transport emissions which are being considered or have been implemented by governments in Canada, including carbon taxes, gasoline taxes, a clean (low carbon) fuel standard, a zero emission vehicle standard, and electric vehicle subsidies.

The model is based on a standard micro-economic framework, which allows us to estimate the

[1] The *Pan-Canadian Framework* (`http://publications.gc.ca/site/eng/9.828774/publication.html`) outlines four potential actions in addition to carbon pricing to reduce emissions from the transport sector. We focus on the zero emission vehicle strategy and the clean fuel standard, which have received the most attention. At the time of writing, both policies remain under development, such that details are not available.

costs of various policies using accepted measures. Moreover, the general equilibrium nature of the model allows us to consider—in a simple manner—the way in which policies in the transport sector interact with taxes that are already in place in the broader economy, which economists have shown is important to evaluating the costs of an environmental policy (Goulder et al., 1999; Parry et al., 1999). We use our estimate of costs to simulate the impact of a variety of policies that reduce transport sector emissions by up to 20% over a medium-run (approximately 5 year) period. We are particularly interested in comparing the cost effectiveness of regulatory approaches to reducing emissions—such as a clean fuel standard or a zero emission vehicle standard—with market- based approaches, such as a carbon tax. This issue is important in Canada at the moment because the federal government is currently in the process of designing new regulations to reduce greenhouse gas emissions from the transport sector and because recent research is divided on the cost-effectiveness of these different approaches (Vass and Jaccard, 2017; Holland et al., 2009).

We have two main findings. First, we simulate a number of individual climate change policies targeting the passenger transport sector. We find—as expected—that a carbon tax is a much more cost-effective approach to reducing emissions compared to other policies, including a fuel economy regulation, clean fuel standard, or zero emission vehicle mandate. Whereas the *average* cost of emissions reductions achieved under a carbon tax is about $175 per tonne to reduce emissions by about 10%, the average cost for a fuel economy regulation, clean fuel standard, or zero emission vehicle mandate are all between $200 and $1,000 per tonne. Moreover, the average cost for a carbon tax can be substantially reduced if it is made revenue neutral, such that revenues from the carbon tax are used to reduce other taxes. In this case, our analysis suggests that the cost of emission reductions falls to $110 per tonne. The carbon tax emerges as the most cost effective policy because it takes advantage of the maximum number of channels to reduce emissions. The carbon tax provides incentives to travel less, to switch modes from private car to other less greenhouse gas intensive modes, to use lower-carbon fuels, and to buy more fuel-efficient vehicles. None of the other policy instruments provide all those incentives.

The economic advantage of carbon taxes relative to other policies has been well known for some time, and so our first findings are not surprising. Despite their clear economic advantages, however, it is politically difficult to impose high carbon taxes. Policy makers instead often turn to other regulations, which may be less politically controversial. In practice, policy makers typically impose multiple regulations to reduce greenhouse gas emissions—this is the approach being proposed by the Canadian federal government. The advantage of multiple regulations over individual regulations is that they can target more margins for reducing greenhouse gases than individual regulations, and so better approach the cost-effectiveness of a carbon tax. Our second research question focuses on how government should design its forthcoming package of regulations to be as cost effective as possible. In particular, assuming the Pan-Canadian carbon pricing benchmark is not changed, how should government choose the forthcoming zero emission vehicle policy and clean fuel standard? We find that there is a role for both instruments in reducing emissions, and that when they are used together, they achieve substantially improved cost-effectiveness compared to when either instrument is imposed on its own. Our model suggests that to be as cost-effective as possible, most of the abatement required for most reduction targets should come from the clean fuel standard, but we find that a modest zero emission vehicle mandate is a recommended part of the package, particularly when the reduction target is tighter. Even with the optimal combination of regulatory policies, however, we still find that a revenue-neutral carbon tax is substantially more cost-effective for reducing emissions than a regulatory approach.

The rest of the paper proceeds as follows. In the next section, we outline key trends in greenhouse gas emissions in the passenger transport sector. This helps to convey the magnitude of challenge facing policy makers in generating deep greenhouse gas reductions. In Section 3 we explain the model that is used to estimate the impacts and costs of a wide variety of public policies aimed at reducing transport sector emissions. In Section 5 we go through the results that emerge from our analysis. Finally, in Section 7 we provide a discussion of the results, and some general conclusions, which we hope are useful to the on-going development of decarbonization policies in the transport sector in Canada.

2 Greenhouse gas emissions from passenger transport

Greenhouse gas emissions from on-road passenger transport reached about 75 Mt CO_2e in 2014, representing about 11 percent of total emissions in Canada.[2] This source of greenhouse gas emissions has grown by about 10% between 1990 and 2014. However, encouragingly, emissions have been stable in the sector since about 2002.

It is useful to decompose the overall change in passenger vehicle greenhouse gas emissions in order to understand the relative importance of various drivers. We can do this by using a simple identity to capture key trends that affect GHG emissions from the passenger vehicle sector:[3]

$$\text{GHG} = \text{Population} \times \underbrace{\frac{\text{Road travel}}{\text{Population}}}_{\text{Reduce travel}} \times \underbrace{\frac{\text{Private travel}}{\text{Road travel}}}_{\text{Mode switch}} \times \underbrace{\frac{\text{Fuel}}{\text{Private travel}}}_{\text{Improve fuel efficiency}} \times \underbrace{\frac{\text{GHG}}{\text{Fuel}}}_{\text{Decarbonize fuels}} . \tag{1}$$

The identity breaks down overall greenhouse gas emissions from on-road passenger transport into five key explanatory variables: the population, the demand for on-road travel per person, the share of total road travel in private vehicles, the amount of fuel used per kilometre of private travel, and the average greenhouse gas intensity of fuel. The identity posits a simple relationship between each variable on the right hand side and the left hand side outcome. For example, if demand per person for private vehicle travel increases by a factor of 1.5, the identity projects that overall greenhouse gas emissions will increase by the same factor.

The identity helps to highlight key ways in which transport sector emissions can be reduced (in blue, below equation (1)). In particular, taking population as given, transport sector emissions can be reduced by a combination of four potential actions: 1. by reducing overall travel demand per person, 2. by switching from high-carbon to low-carbon transport modes (e.g., car-pooling, public transport, and active transport), 3. by improving the fuel efficiency of on-road vehicles,

[2]Natural Resources Canada, Comprehensive Energy Use Database. These figures only include emissions released by combustion in the transport sector, and do not include the upstream emissions required to produce fuel. We do include upstream emissions in the model that is described later in this report. Including upstream emissions increases total transport sector emissions to about 86 Mt CO_2e.

[3]For simplicity, this identity ignores GHG emissions from public transit. We include these emissions in our model later in the paper.

and 4. by reducing the greenhouse gas emissions produced when a unit of fuel is used. Later in the paper, we show how alternative transport policies encourage these types of greenhouse gas reducing actions. In the following paragraph, we show how past actions have contributed to overall changes in greenhouse gases.

Using data from Statistics Canada and Natural Resources Canada, Figure 1 shows how each of the key drivers of private vehicle greenhouse gas emissions has evolved since 1990. First, population has grown by nearly 30 percent since 1990, contributing to an increase in demand for transport, and thus increasing greenhouse gas emissions. In addition, individual travel demand (i.e., the average road travel per person) has increased by about 10 percent over the same period. The figure highlights that on-road passenger travel demand per person has been relatively flat since about 2002, however. Data in a number of other developed countries show a similar flattening of the growth rate in on-road passenger travel demand over the same period (although passenger travel has increased significantly in the US since the fall in oil and gasoline prices after 2013 (Leard et al., 2016)). These two demand factors have together exerted significant upward pressure on GHG emissions. Without any other changes, increases in population and the average distance travelled per person would have resulted in an increase in on-road greenhouse gas emissions by about 40 percent since 1990. However, at the same time as demand for passenger travel has increased, a number of other factors have worked together to help reduce overall GHG emissions from on-road passenger travel. First, and most importantly, vehicles have become much more fuel efficient since 1990. In particular, Figure 1 highlights that the stock of private vehicles uses about 17 percent less fuel to move a passenger one kilometre in 2013 compared to 1990. Alongside this change, the greenhouse gas intensity of fuel has improved by about 4 percent relative to 1990, as regulations and other policies governing the use of renewable fuels in gasoline and diesel have entered into force.[4] As well, the figure shows that there has been a slight decrease in the share of private travel in total on-road passenger travel, reflecting a slight increase in the mode share of public and active transport in Canada. This has likely reduced private vehicle greenhouse gas emissions by about

[4]Note that there is debate about the life cycle greenhouse gas emissions from some renewable fuels such as ethanol.

2-3 percent since 1990. Together, these improvements in vehicle fuel efficiency, greenhouse gas intensity, and changes in mode share have exerted substantial downward pressure on total private on-road GHG emissions. Without demand growth, they would have caused a 22 percent reduction in GHG emissions from on-road private vehicles since 1990. Overall, greenhouse gas emissions from on-road private transport have grown by about 10 percent since 1990, as shown by the thick black line in the figure.

To achieve substantial reductions in emissions, it will be necessary to significantly increase the rate of improvements in vehicle fuel economy, increase the share of public and active transport, reduce the greenhouse gas intensity of fuel, and/or reduce overall travel demand. Since population continues to grow by over 1 percent annually, these improvements will need to be rapid and sustained to overcome the on-going changes in population. For example, Canada's Paris commitment requires a 30% reduction in greenhouse gas emissions relative to 2005 levels by 2030. GHG emissions from on-road passenger transport in 2014 were about 1.5% below 2005 levels, such that they must fall by roughly 2% per year until 2030 to hit the Paris target.[5] Given an on-going increase in population of over 1% per year, the reduction in per capita GHGs from transport will need to reach roughly 3% per year. For reference, the reduction in per capita GHG emissions since 2005—a period of rising oil prices and the introduction of new vehicle greenhouse gas regulations—was only about 1% per year (shown by the dashed line in Figure 1). This highlights the need for aggressive policies in order to substantially reduce GHG emissions from passenger transport.

2.1 Policy options for reducing greenhouse gas emissions

Governments have a wide range of policies at their disposal for addressing greenhouse gas emissions from passenger vehicles, and governments in Canada have been relatively pro-active in experimenting with these (though there remain many policy options in the transport sector that Canadian governments have not used extensively, notably including distance-based taxes or charges and

[5]The Paris target applies to total emissions, not to emissions from on-road transportation specifically, but this still provides a useful benchmark for analysis.

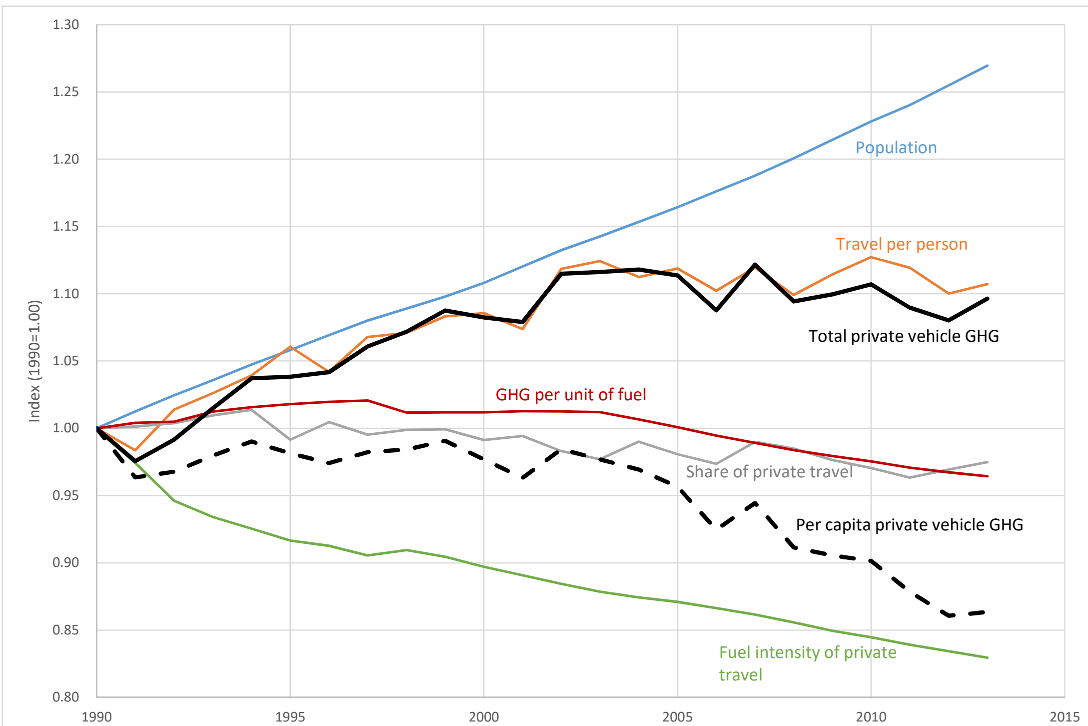

Figure 1: Decomposition of on-road private vehicle greenhouse gas emissions. Calculations by authors using data from CANSIM 0051-0001 and Natural Resources Canada's Comprehensive Energy Use Database.

congestion charges; our analysis does not include policies designed to address urban form). In the following section, we outline the model that we use to simulate these various policies. Here, we provide a brief description of the experience in Canada with these policies.

Carbon tax A tax (or price) on carbon dioxide emissions provides a market-based incentive that can help to induce emitters to account for the social cost of greenhouse gas emissions in making transport decisions. In theory, a carbon tax provides equivalent incentives for reducing greenhouse gas emissions in all transport-related decisions, which helps to make it a relatively cost-effective policy. It is possible for revenue from a carbon tax to be used to reduce other taxes in the economy, provide offsetting rebates to low-income or other households, or increase investment in low-carbon infrastructure. Carbon prices have been applied on transport fuels in British Columbia, Alberta, Ontario, and Quebec. The *Pan-Canadian Framework on Climate Change* stipulates that all provinces must have carbon prices in place by 2018, increasing from \$10/t CO_2 to \$50/t by 2022.[6]

Fuel tax Fuel excise taxes have been applied in Canada (and other countries) at the provincial, municipal, and federal levels for several decades. They have typically been implemented as a revenue generation tool, but because the consumption of gasoline is closely tied to greenhouse gas emissions as well as a number of other social costs (accidents, congestion) they can play a role in reducing greenhouse gas emissions.

Low carbon (clean) fuel standard/renewable fuel standard Governments across Canada, at both the federal and provincial levels, have implemented renewable fuel standards to promote the blending of renewable fuels such as ethanol and biodiesel into gasoline and diesel, respectively. Renewable fuel standards specify a minimum proportion of renewable fuels to be included in overall fuel sales. A closely related policy is the low carbon fuel standard, which has been implemented in British Columbia (as well as California). A low carbon fuel standard specifies a maximum life cycle emissions level for the overall fuel mix. The

[6] Details of the carbon price are provided in the Technical Paper.

Pan-Canadian Framework envisions a low-carbon fuel standard playing a significant role in reducing greenhouse gas emissions from the transport sector.[7]

Fuel economy and greenhouse gas intensity regulations The Canadian federal government has used fuel economy and greenhouse gas intensity regulations to help reduce fuel consumption and greenhouse gas emissions from new vehicles for several decades. These regulations can be effective in reducing the greenhouse gas emissions intensity of new vehicles, but do not affect the older vehicle stock, and do not provide incentives to reduce driving or choose lower carbon fuels. The existing passenger vehicle greenhouse gas intensity standards are indexed to vehicle size (i.e., become less stringent for larger footprint vehicles), which implicitly provides a subsidy for larger cars, rendering the policy less cost-effective in reducing emissions (Anderson et al., 2016).

Electric vehicle subsidies For several years, British Columbia, Ontario, and Quebec have offered large subsidies to stimulate the purchase of electric vehicles. Consumers appear to have responded to these policies, with electric vehicle market shares in these provinces substantially above those of other provinces.[8] Electric vehicle subsidies promote low-carbon vehicle technology, but do not induce consumers to reduce driving or switch modes.

Zero emission vehicle regulations Quebec has recently implemented a zero emission vehicle mandate, which requires that zero emission vehicles make up a given percentage of new vehicle sales by 2025. Quebec's policy is modeled on a similar policy in California. The federal government has announced the development of an electric vehicle strategy, which could take the form of a zero emission vehicle mandate.

[7]Discussions are currently underway regarding the potential design of this policy. See the Environment Canada Discussion Paper for details.

[8]Electric vehicle sales in 2016 made up 0.7% of total vehicle sales in Ontario, Quebec, and British Columbia, but only 0.1% of sales in other provinces.

2.2 Cost-effectiveness

To consider the cost-effectiveness of these various policies that reduce greenhouse gas emissions from the transport sector it is useful to reconsider the four possible pathways by which greenhouse gas emissions can be reduced: by reducing overall travel demand, promoting mode switching from private transport to public transport (or other transport options such as walking and cycling), improving fuel economy, and decarbonizing transport fuels. Each of these decarbonization options has associated costs, and the marginal costs of actions in each of these categories are likely to rise as the reduction target rises.

Consider a carbon tax—the benchmark against which we compare other policies. As is well-known, the carbon tax provides consumers with incentives to reduce carbon emissions via each of the actions, provided the marginal cost of the action is lower than the carbon tax. By contrast, none of the other instruments exploit all the potential channels for decarbonisation that a carbon tax does. This is a key reason that the carbon tax is favoured by many economists.

Consider now an alternative policy—for example, an electric vehicle (EV) mandate. An EV mandate requires a certain proportion of new car buyers to purchase an electric vehicle rather than an internal combustion vehicle. It does not reduced travel demand.[9] Likewise it does not induce switching between transit and driving. Finally, it provides no incentive to decarbonize the fuel stream. Because it only operates on one margin of decarbonization actions, reducing emissions using a policy such as an EV mandate tends to be relatively expensive compared to a more broadly-targeted policy such as a carbon tax.

What about a combination of policies?—for example consider a combination of a low carbon fuel standard and a fuel economy regulation. The low carbon fuel standard provides incentives for consumers to decarbonize fuel choices, while the fuel economy regulations provide incentives for consumers to choose more fuel efficient vehicles. Neither policy directly provides incentives for consumers to switch to lower carbon transport modes or to reduce overall transport demand.[10] As

[9] Indeed to the extent that electric vehicles have lower cost per kilometre travelled, there is likely to be at least some rebound effect on kilometres travelled.

[10] Either or both policies may indirectly provide incentives for consumers to switch transport modes or reduce overall

a result, to achieve the same amount of emission reductions as the carbon tax, this combination of policies must push further to decarbonize fuels and to improve the efficiency of vehicles than the carbon tax.

In theory, it is possible for a policy maker to design a combination of policies to mimic the outcomes and costs associated with a carbon tax (see Fullerton and West, 2002), by choosing a policy package that incentives an optimal combination of decarbonization options. We build on this insight later in the paper, to evaluate how the forthcoming package of government regulations could be designed to be as cost-effective as possible. However, without knowing the shape of marginal abatement curves for different actions, it can be difficult for the policy maker to correctly estimate appropriate stringency of multiple carbon tax substitutes required for cost-effective emissions abatement. This is further complicated by the fact that there may be interactions among the policy instruments such that the effect of one instrument is to enhance the response to another instrument. We return to this consideration in our discussion of policy 'packages.'

We summarize the direct incentives generated by each type of public policy in Table 1. As stated above, a carbon tax—by increasing the price associated with carbon emissions—provides incentives for decarbonization across all four potential actions. A fuel tax is similar, but provides less incentives for decarbonizing fuels, since in Canada excise taxes do generally do not differentiate between renewable fuels and gasoline (when the two are blended).[11] Fuel economy regulations require manufacturers to improve new vehicle fuel economy, but may actually cause increases in travel demand, as more fuel efficient vehicles are cheaper to drive. Similar incentives are generated by a low emission vehicle mandate or by subsidies on low emission vehicles. A low carbon fuel standard requires improvements in the greenhouse gas intensity of fuels. If this requirement indirectly causes increases in fuel prices, this policy can have indirect effects on other decarbonization actions.

Two conclusions can be drawn from this discussion. First, unless there are significant indirect

transport demand, as a consequence of the equilibrium impacts of the policies on various prices faced by the consumer. We consider these indirect impacts of policies in our formal model, but focus on the direct impacts of the policies here.

[11] Governments have in the past used excise tax exemptions to promote ethanol blending in Canada, but have phased these policies out and replaced them with ethanol production subsidies (Laan et al., 2009).

Policy	Reduce travel demand	Induce mode switching	Improve fuel economy	Decarbonize Fuels
Carbon tax	yes	yes	yes	yes
Fuel tax	yes	yes	yes	no[a]
Fuel economy regulations	no	no	yes[b]	no
Electric vehicle mandate	no	no	yes	no
Low carbon fuel standard	no	no	no	yes
Public transit subsidies	no	yes	no	no

Table 1: Direct incentives to reduce transport GHG emissions generated by alternative policies

[a] A fuel excise tax provides incentives for consumer to switch from fuels to electricity, but not from one liquid fuel to another.

[b] Fuel economy regulations require improvements in the new vehicle fleet, but not in existing vehicles.

effects on relative prices caused by any of these individual policy options, pursuing deep decarbonization with a policy that is not a carbon tax is likely to be relatively expensive, because it does not provide incentives across all potential decarbonization pathways. Second, although individual policies do not provide incentives across all decarbonization pathways in the same way as a carbon tax, it may be possible to implement combinations of policies that do (Fullerton and West, 2002). For example, from Table 1, it is apparent that a fuel tax and a low carbon fuel standard provide incentives across the range of decarbonization actions. A carefully-chosen combination of these two policies is therefore likely to approximate the cost-effectiveness of a carbon tax. We quantitatively evaluate potential combinations of policies in our analysis later in the paper.

3 Model

We develop a parsimonious model of on-road private travel to represent policy options for reducing greenhouse gas emissions in the transport sector. The model retains key aspects of the economy necessary to represent the suite of policy options for reducing GHG emissions from on-road transport. However, in order to keep the model simple and transparent, a number of complexities associated with more complicated models and the real economy have been omitted.

The model shares similarities with a number of other similar efforts to model the transport system, in order to compare alternative decarbonization policies in the transport sector. Anderson et al. (2016) uses a partial equilibrium model of the US transport sector. That model includes the potential for cost reductions in immature renewable fuels over time (such as cellulosic ethanol),[12] but does not include electricity as a potential transport fuel, and does not consider interactions between transport policy and the rest of the economy. Anderson et al. (2016) find that a carbon tax, fuel tax, or fuel economy regulation can all cost-effectively reduce greenhouse gases, but that existing policies are considerably less cost effective. They report that a low carbon fuel standard and especially a renewable fuel standard are particularly costly policies to reduce greenhouse gases. Holland et al. (2009) focus on the evaluation of a low-carbon fuel standard, and note that the implicit subsidy to low (but not zero) carbon fuels in the policy produces costly outcomes, and can even produce perverse outcomes in which greenhouse gas emissions are increased under the policy (although this outcome is unlikely). Fullerton and West (2002) examine how policy makers can substitute for cost-effective carbon taxes with a combination of other instruments using a model similar to the one presented here. Fischer et al. (2007) develop a simple economic model of consumer transport choice similar to the model developed in this paper, and use it to evaluate whether fuel efficiency standards should be tightened. Vass and Jaccard (2017) develop a partial equilibrium simulation model of the Canadian transport sector and focus on long-term decarbonization using a low-carbon fuel standard. Their model does not explicitly calculate the costs of alternative transport policies,

[12] Cost reductions through learning-by-doing spill over in part between countries and so are less important for small countries such as Canada.

but Vass and Jaccard (2017) conduct some back-of-the-envelope calculations to suggest that the cost of a low carbon fuel standard is unlikely to be significantly larger than a carbon tax, given their assumptions. The result appears to be driven in part by optimistic assumptions about alternative fuels relative to other papers in the literature.

The model in this paper consists of a representative household that uses transport services. Transport services can be obtained from either public transport or private transport. Private transport can be provided by a number of different types of vehicle technologies—for example, conventional vehicles with internal combustion engines, gasoline-electric hybrid vehicles, and electric vehicles. Each type of vehicle, as well as public transport, is produced using both a fuel composite as well as non-fuel inputs. Several types of fuel are available, including relatively clean fuels, such as biofuels and electricity, and the conventional fuels, gasoline and diesel. Each fuel produces a different amount of greenhouse gas emissions during its life cycle (from extraction to combustion).

To reduce greenhouse gas emissions from on-road transportation, consumers can switch to more fuel efficient vehicles, use lower carbon fuel, switch from private to public transport, or reduce their overall demand for transport. They are motivated to undertake these actions by policies implemented by the government.

The model does not explicitly capture the slow turnover of the vehicle stock over time. Instead, to keep the model simple it is a comparative static model which captures counterfactual scenarios at a point in time, and does not model the transition to that point over time. We approximate a more complicated stock turnover model by including an existing vehicle stock as a consumer endowment. By varying the size of the existing vehicle stock with respect to the total vehicle stock, we can approximate different time horizons in model simulations.

Before describing the model, it is worth noting what the model does *not* include. First, the model assumes a rational consumer. While this is typical, it is an assumption that is sometimes questioned in analyses of transport. For example, Anderson et al. (2016) assumes that consumers undervalue fuel economy, such that regulations that promote improvements in fuel economy can be welfare-improving (before even taking into account environmental benefits). The literature does not provide clear findings on whether consumers fully value fuel economy improvements. However, three recent papers are all unable to reject the hypothesis that consumers fully value fuel economy, so our assumption is not at odds with the recent evidence (Busse et al., 2013; Allcott and Wozny, 2014; Sallee et al., 2016). Second, while the transport sector produces a significant amount of transport emissions, which are the focus of this paper, it also generates other externalities, such as accidents, congestion, and local air pollution.[13] Many of these externalities would be affected by the polices that we simulate here, and this could affect the estimated costs and benefits of policies. To keep things simple, however, these are not included in the current paper. As a result, our paper likely overestimates the net costs of policies that reduce greenhouse gas emissions. Third, when modeling the choice between alternative transport technologies, we take the technologies as exogenous: that is, we do not model innovation and improvement of technology in the model, as in Anderson et al. (2016). This will likely not have major effects on our results given that our focus is on Canada (which is a small country, and thus mostly a taker of vehicle technology), but again could lead our estimates of the benefits of some policies to be underestimated. Fourth, we do not consider network effects that could be associated with transport policy, and in particular with new technologies. For example, public transport may be more effective (due to higher frequency service) as ridership increases, and consumer experience with new technologies such as electric vehicles may spill over to others. This omission will lead us to undervalue policies that directly promote such technologies.

The model is set up as a decentralized computable general equilibrium model, and is solved with the PATH solver as implemented in GAMS. In the following sub-sections, we describe the model in more detail.

[13]For example, Wood (2015) estimates that these externalities are several times larger than the greenhouse gas externality in the Greater Toronto Hamilton Area.

3.1 Consumers

The model is based on the transportation decisions of a representative consumer. The consumer has an endowment of labour, which is denoted $\bar{L}$.[14] The consumer gains utility from consuming leisure (L_H) and market goods (M). There are two types of market goods - transport services (T) and other goods (X). Overall consumer utility (U) is therefore given by:

$$U = U(L_H, M(T, X))$$

Transport services are produced from either public transport (P) or private transport (D, for driving), such that $T = T(P, D)$. The following sections explain the public transport and private transport technologies and associated consumer preferences.

The consumer obtains market income from its endowment of $\bar{L}$ as well as from any transfers of tax revenue (R) that government raises from taxes imposed on labour, vehicles, or fuel that are described in the following sections. The pre-tax wage rate is w, and the tax rate on income is tl, such that the consumer market income is $I = (\bar{L} - L_H)w\frac{1}{1+tl}$. The consumer budget constraint is therefore:

$$p_D D + p_P P + X = (\bar{L} - L_H)w\frac{1}{1+tl} + R,$$

where the price of good X is the numeraire, and where p_D and p_P are the prices of driving and public transit, respectively.

3.2 Public transport

Public transit is provided by the combination of public transit infrastructure and fuel, such that $P = P(L_P, F_P)$. We capture the non-fuel inputs to public transit by the inputs of labour required to produce those goods, L_P. We capture fuel inputs to public transit in F_P, a composite of the fuels

[14] For simplicity, we do not distinguish between types of factors of production (i.e., capital vs. labour; high-skill vs. low-skill labour; etc.) and instead subsume all factors of production into $\bar{L}$.

used in the transit sector. More detail about the fuels composite for the public transport sector, follows.

3.3 Private transport

Like public transport, private transport is generated by the combination of non-fuel inputs and fuel inputs. However, in the case of private transport, we also model the potential for different types of vehicles to produce transport services, as well as the potential for vehicle fuel efficiency improvements. In particular, private transport services can be generated by driving any of a number of classes of vehicles, denoted by the set $v = \{1 \ldots, V\}$. Each vehicle class v can use a different combination of fuel and non-fuel inputs, and each vehicle class uses a different fuel composite, such that $D_v = D_v(L_v, F_v)$, where the arguments represent the non-fuel and fuel inputs to vehicle v, respectively. Although the technology determines the possible combinations of non-fuel and fuel inputs, consumers are able to substitute non-fuel for fuel inputs in response to changes in relative price. This allows consumers to select the energy efficiency of their vehicle. Details of the calibration are provided below. Overall private transport demand is then satisfied by these multiple different classes of vehicles, such that: $D = D(D_1, \ldots, D_V)$. Transport services from each vehicle are generated by the combination of fuel and non-fuel inputs as discussed in more detail in section 3.8.2.

One of the vehicle classes refers to the extant stock (fleet) of vehicles. In this case, the vehicles are an existing stock with fixed characteristics, such that the ratio of fuel to non-fuel costs is fixed (similar to the way in which transit is modeled).

3.4 Fuels

Table 2 lists the individual fuels that can be used to provide transport services. We index these fuels by the set $f = \{1, .., F\}$. Each fuel is produced using labour, and we represent the resource requirements of different fuel types by different labour input requirements labour in the production of one unit of fuel. Each fuel additionally produces a different amount of greenhouse gas emissions.

We track greenhouse gas emissions throughout the entire fuel life cycle, from upstream production to eventual combustion. The fuel production technology is therefore given by $G_f = G_f(L_f, Z_f)$, where L_f and Z_f are labour inputs and greenhouse gas "inputs" to production, respectively. Our model does not capture the possibility for endogenous changes in the life cycle emissions or costs of different fuels, so the resource requirements and emissions for each fuel type are fixed.[15]

We identify three fuel composites of the individual fuels. One is used by new combustion vehicles (internal combustion or hybrid), one is used by public transit and one (comprising only electricity) is used by the new electric vehicles. Other key features of these composites include that: 1. the transit composite has a high share of diesel, 2. the extant fleet composite has a high share of gasoline, and 3. the extant fleet composite has a very small share of electricity.

Private and public transport demand for the fuel composites is given by: $F_v = F_v(G_1, \ldots, G_F)$ and $F_P = F_P(G_1, \ldots, G_F)$, respectively. The functions F_v and F_P represent the mapping from fuel composites to vehicle technologies, and capture the potential substitutability between different fuel types in different applications. The elasticites of substution among intermediate fuel composites (ethanol, diesel and gasoline for example) are denoted σ_F^v.

3.4.1 Blend Limits and Intermediate Fuel Composites

In the case of diesel and ethanol there is an added layer of substitution. While ethanol derived from corn and ethanol derived from cellulose is identical in use, the unit costs of production and emission factors differ. Similarly biodiesel produced by different means (canola, HDRD for example) has differing costs and emissions factors. In both cases, there are blend limits that limit the penetration of the individual fuels into the fuel composites $G_1, \ldots, G_F$. Substitution among the individual fuels within an intermediate composite is very easy, but fuels are subject to blend limits. In the case of fuels other than ethanol and biodiesel, the intermediate nests include only a single fuel. Substitution among fosil fuels within the intermediate nest has a constant elasticity of substitution of σ_f^G.

[15] i.e., G_f is a Leontief function.

In the case of ethanol, most vehicles will only work with a maximum of 15% in gasoline. In the case of conventional biodiesel the limit is 5% in diesel, whereas HDRD can account for up to 40% of 'diesel.' Since only a small subset of vehicles (existing and new) can burn gasoline with higher ratios of ethanol, and since our focus is on the near term, we do not allow higher blend ratios.

Fuel	Description	I Nest
pet	Gasoline from petroleum	pet
dsl	Diesel from petroleum	dsl
eth	Ethanol (most from corn	eth
ethcel	Cellulosic ethanol	eth
biodslr	Biodiesel from rapeseed/canola	dsl
HDRD	Hydrogenation Derived Renewable Diesel	dsl
pro	Propane	pro
ngas	Natural Gas	ngas
ele	Electricity	ele

Table 2: Fuels included in the model

3.5 Rest of economy

The remainder of the economy uses inputs of the factor of production to produce the market good, such that $X = L_X$.

3.6 Government

The only role of government in this simple model is collecting taxes and redistributing revenues back to the household, and setting other non-tax policies. In the model, the government imposes the tax rate tl on market income. The government can also introduce a number of policies—as described in the prior section—with the aim of reducing greenhouse gas emissions from public transport. First, it can introduce a carbon tax, given by τ. The carbon tax is imposed on the (life cycle) emissions of all of the fuels. The government can also impose taxes on individual fuels f, given by β_f. These taxes can be positive or negative, with negative taxes representing a subsidy. As shown in Holland et al. (2009), it is possible to use a combination of taxes and subsidies on clean and dirty fuels to represent both a low carbon fuel standard and a renewable fuel standard. Government can also impose a tax rate γ_v on vehicles of type v. Once again, this tax can be positive or negative. A negative tax can be used to represent a subsidy, for example, on electric vehicles. A revenue-neutral combination of taxes and subsidies can be used to represent a fuel economy or greenhouse gas intensity standard as well as a zero emission vehicle standard. Finally, government can impose a tax on public transport, which is given by ζ (again, a negative value represents a subsidy). The combination of these tax and subsidy parameters is sufficient to represent a broad array of transport policies that are currently being considered or have been implemented by Canadian governments.

We do not explicitly model government spending, so revenue collected by the government on taxes is rebated back to the consumer in lump sum (unless otherwise specified). The rebate of tax revenue to the consumer is therefore:

$$R = \frac{tl}{1+tl} w(\bar{L} - L_H) + \sum_F Z_f(\tau + \beta_F) + \sum_V \beta_V L_V + \zeta P.$$

3.7 Market clearance

Markets for all goods clear in the model, such that in the factor market:

$$\bar{L} = L_H + L_X + L_P + \sum_V L_V + \sum_F L_F.$$

In addition, prices for each fuel and vehicle adjust such that the supply and demand for each fuel type and vehicle are equal.

3.8 Parameterization and functional forms

The prior description of the model focused on the general relationships between variables in the model, but did not impose particular functional forms, and did not specify parametric assumptions. These are critical in measuring the social costs and benefits of alternative transport policies. In this section, we explain these assumptions and also describe sources of data underlying our parametric assumptions. Given the uncertainty associated with some of our parametric assumptions, we provide a comprehensive sensitivity analysis when we simulate the impacts of transportation policies.

3.8.1 Consumer utility function

The utility function is a constant elasticity of substitution (CES) function, which takes the form:

$$U = \left(\alpha_U (L_H)^{\frac{\sigma_U - 1}{\sigma_U}} + (1-\alpha_U) M^{\frac{\sigma_U - 1}{\sigma_U}} \right)^{\frac{\sigma_U}{\sigma_U - 1}},$$

where σ_U is the elasticity of substitution between leisure and market goods, and α_U is a distribution parameter. Ballard (2000) shows how these two unknown parameters can be chosen such that the utility function reflects a specified set of labour supply elasticities, which can be taken from empirical evidence. In this model, we choose σ_U and α_U to reflect a compensated labour supply elasticity of 0.3 and an uncompensated elasticity of labour supply of 0.05. These values are consistent with empirical evidence (Cahuc et al., 2014). We set the initial tax rate on factor income at $tl = 0.4$, which roughly reflects the size of government as a share of total gross domestic product in Canada. This initial tax rate creates a distortion in the labour market. The distortion can make imposing environmental regulations more costly, but opens up the possibility for recycling of revenue from an environmental tax to improve both environmental and economic outcomes (Goulder et al., 1999; Parry et al., 1999).

In a similar manner, the consumer choice between transport services and other market goods is given by a CES function, as is the choice between private and public transport:

$$M = \left(\alpha_M (X)^{\frac{\sigma_C - 1}{\sigma_C}} + (1-\alpha_M) T^{\frac{\sigma_C - 1}{\sigma_C}} \right)^{\frac{\sigma_C}{\sigma_C - 1}},$$

$$T = \left(\alpha_T (P)^{\frac{\sigma_T - 1}{\sigma_T}} + (1-\alpha_T) D^{\frac{\sigma_T - 1}{\sigma_T}} \right)^{\frac{\sigma_T}{\sigma_T - 1}}.$$

There are four unknown parameters in these functions: the elasticity of substitution between transport and other goods (σ_C), the elasticity of substitution between private and public transport (σ_T), and the share parameters α_M and α_T, which are based on the benchmark expenditure shares. We obtain data on benchmark consumer expenditures on transport as a share of total expenditures and benchmark public transport expenditures as a share of total transport expenditures from Statistics Canada's Survey of Household Spending.[16] Determination of the substitution other parameters is discussed below.

3.8.2 Vehicle choice

Consumers choose amongst driving different classes of vehicles, indexed by v. In order to capture the slow turnover of the vehicle stock, we model the existing vehicle stock as well as the new vehicle stock. Specifically, consumers are initially assumed to have a fixed endowment of existing vehicles, which has fixed characteristics (e.g., fuel economy) and can be used to satisfy transport demand. By varying the proportion of existing vehicles, we are able to model the slow turnover of the existing vehicle fleet in a simple way. In our main simulations, consumers have an endowment of existing vehicles sufficient to satisfy 50% of their total private travel demand, with the remaining 50% satisfied by new vehicles. Our model therefore reflects a medium-run time frame of about 7 years, as shown in Figure 2.

We model three classes of new vehicles in addition to the existing vehicle stock: 1. vehicles with gasoline internal combustion engines, 2. vehicles with hybrid battery-electric gasoline engines, and 3. vehicles with electric motors only. The first two of these vehicles, as well as the existing vehicle stock, consume gasoline or other liquid fuels (see next section), while the third consumes electricity only. The consumer chooses between these three vehicles, with the choice modeled using a constant elasticity of substitution function, with elasticity σ_V:

[16] Available from CANSIM table 203-0021. We use data for the year 2014, the most recent year for which data were available.

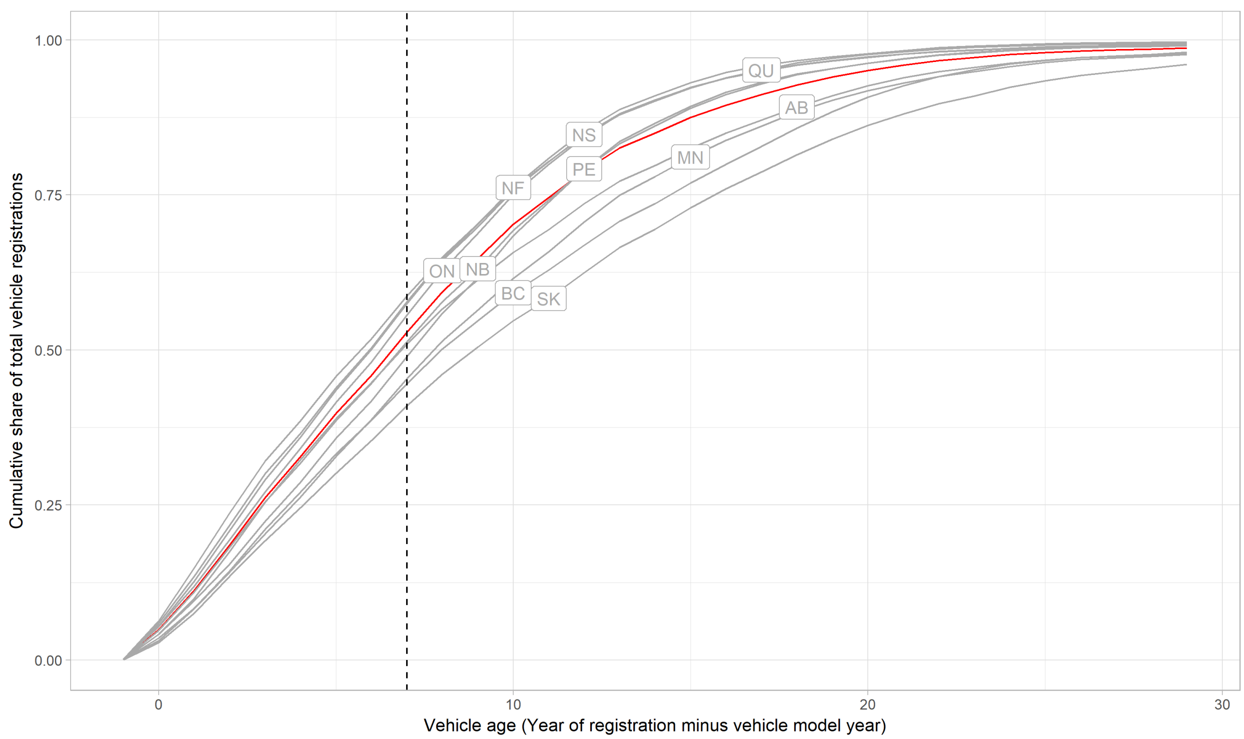

Figure 2: Age profile of existing vehicle stock. Author's compilation based on confidential vehicle registration data obtained from RL Polk and described in Rivers and Schaufele (2017b). Data corresponds to the year 2010.

$$\mathrm{D} = \sum_v \left(\gamma_v (D_v)^{\frac{\sigma_V - 1}{\sigma_V}} \right)^{\frac{\sigma_V}{\sigma_V - 1}}$$

We calibrate this elasticity to match recent Canadian experience on the response to rebates given for hybrid and electric vehicles. Specifically, Chandra et al. (2010) find that a $1,000 rebate for hybrid vehicles increases the hybrid vehicle market share in new Canadian vehicles by about 34%. Assuming a benchmark hybrid vehicle price of $30,000, this suggests an appropriate value for $\sigma_V \approx 9$. Similarly, market shares for electric vehicles in Ontario, BC, and Quebec—where subsidies are available for these vehicles—were about 0.7% in 2016 compared to about 0.1% in other provinces.[17] If the average subsidy in these three provinces is $8,000 and the average electric vehicle costs $42,000, this suggests $\sigma_V \approx 9$. These values provide some preliminary evidence on the choice of this parameter. We set $\sigma_V = 9$ in the main version of the model, and test alternative values in a sensitivity analysis.

Within each of these classes of new vehicles, consumers can choose the fuel efficiency of the vehicle. Consumer preferences for fuel economy are given by the model parameters σ_D^v (the elasticity of substitution between fuel and non-fuel inputs to driving in a given vehicle class v):

$$\mathrm{D}_v = \left(\alpha_v^F (F_v)^{\frac{\sigma_v^D - 1}{\sigma_v^D}} + \alpha_v^K (K_v)^{\frac{\sigma_v^D - 1}{\sigma_v^D}} + \alpha_v^L (L_v)^{\frac{\sigma_v^D - 1}{\sigma_v^D}} \right)^{\frac{\sigma_v^D}{\sigma_v^D - 1}}$$

In the case of driving using an existing vehicle ($v = x$), travel also uses an input of the existing vehicle stock denoted K_x. For all other driving sectors, K_v is zero.

It is important to note that our approach to modeling vehicle fuel efficiency focuses on consumer responses to policies, rather than focusing on manufacturer response, as is done in Anderson et al. (2016); Greene et al. (2005). This is likely appropriate, since Canada is a small enough economy that it's policies are unlikely to drive substantial manufacturer response. However, our assumption may to some degree understate the market response to policies that affect fuel econ-

[17] See data from Green Car Reports at: `www.tinyurl.com/canadaevsales`.

omy. Different classes of vehicles will allow different scope for substitution between fuel and other inputs in producing transportation. For example, in the case of existing vehicle fleet the only ways to improve fuel economy are to drive less aggressively or maintain the vehicle better. By contrast, in new vehicle driving there is also the added choice of purchasing a more or less fuel-efficient vehicle.

3.9 Calibration

We use a search approach to determine the values of σ_C and σ_T and $\overline{\sigma}_D$. There is empirical evidence on the elasticity of vehicle travel with respect to gasoline price (-0.25, taken from Gillingham (2014) and Gillingham and Munk-Nielsen (2016)); the elasticity of gasoline demand with respect to gasoline price (-0.4, taken from (Coglianese et al., 2017)); and the elasticity of public transport with respect to the price of public transport (-0.3, taken from Litman (2004), Paulley et al. (2006), and Rivers and Plumptre (2016). There is also evidence on the cross-price elasticity of transit demand with respect to the price of gasoline (0.1, taken from Litman (2004)). There is also empirical evidence on the elasticity of vehicle fuel economy with respect to gasoline price (Rivers and Schaufele, 2017a; Barla et al., 2009).

We search over values of the parameters σ_C, σ_T and $\overline{\sigma}_D$ to find the best approximation of the four elasticities mentioned in the previous paragraph based on assuming that σ_D^v is the same for all vehicle classes v. The elasticities of substitution between fuel and other inputs for each vehicle class (σ_D^v) are calculated such that the weighted average equals $\overline{\sigma}_D$. We confirm that the resulting overall elasticity of demand for fuel reflects our target value.

3.10 Fuel and Vehicle Data

Information on the unit costs. emission factors and market shares of the fuels are provided in Table 3. The benchmark characteristics of the vehicle technologies included in the model are given in Table 4. Key characteristics of the data are that travel by transit or in a new electric vehicle are both very low emissions and low fuel-cost ways to travel. The worst of our categories in both dimensions is driving in the 'existing fleet' which is dominated by internal combustion vehicles, some of them quite old. Over 90% of passenger kilometres is accounted for by private vehicles, about half that have been bought in the last five years and the other half older. New electric and hybrid vehicles account for 2.4% of passenger kilometres driven.

	Percentage Shares of:				
	Energy (PJ)	Expenditures ($)	Emissions (Mt CO2e)	Unit Cost	g CO2e/MJ
Gasoline (petroleum)	93.8	92.9	94.8	1.00	87
Diesel (petroleum)	3.5	3.2	3.6	0.93	90
Ethanol (corn)	1.7	2.7	1.0	1.62	51
Cellulosic Ethanol	0.0	0.0	0.0	1.95	18
Biodiesel (canola)	ε	ε	ε	1.72	21
HDRD[a]	ε	ε	ε	1.62	43
Propane	0.5	0.9	0.4	1.95	75
Natural Gas	.01	.001	.0003	0.67	57
Electricity	0.5	0.3	.007	0.57	11

ε baseline energy share of biodiesel and HDRD are .00006% of total fuels but .002% of all diesel.

cellulosic ethanol not produced commercially in our baseline

Sources: Ministry of Mines and Energy (2014); Cazzola et al. (2013); Moorhouse (2017); Vass and Jaccard (2017)

[a] Hydrogenation Derived Renewable Diesel

Table 3: Fuel Input Data

	Share (D)	Share (T)	g/pkm	F/km	θ_C^F
Transit		6.2	0.5	0.4	8.7
Existing Fleet	50.0	46.9	1.3	1.1	24.7
New Internal Combustion	47.5	44.5	1.2	1.0	22.1
New Hybrid	2.0	1.9	0.8	0.7	14.8
New Electric Vehicle	0.5	0.5	0.1	0.4	8.1

Share (D) Share of private vehicle passenger-kilometres driven by class of vehicle

Share (T) Share of all passenger-kilometres by vehicle class and transit

g/pkm emissions intensity (grams CO2e per passenger kilometre)

F/km Relative energy intensity passenger kilometres (normalized to 1 for new internal combustion vehicles)

θ_C^F cost share (%) of fuel in transportation by vehicle sector and transit

Table 4: Overview of Vehicle Technology

4 Scenarios

We use the model to estimate the costs and potential environmental impacts of various policies designed to reduce transport sector emissions. We conduct two main simulation exercises. First, we simulate transport policies individually, and compare the costs imposed by each policy to reach a given level of emission reductions. We vary the stringency of each policy in order to allow us to calculate the implied marginal abatement cost associated with achieving various emission reduction targets with each policy. This is a useful exercise, as it allows us to directly compare policies against one another.

Real-world policy however, typically does not feature individual policies. Instead, policy-makers often use a combination of policies to achieve a policy goal. This approach is being pursued in Canada, where renewable and low carbon fuel standards, carbon and gasoline taxes, electric vehicle subsidies and mandates, public transit credits, and fuel economy regulations are applied together to reduce greenhouse gas emissions from transport. Our earlier analysis suggests a potential benefit of this approach—by providing incentives for undertaking various decarbonization actions, a combination of policies may be more cost effective than an individual policy (excepting a carbon tax, which already provides incentives for reducing emissions across different categories of actions).

As a result, we estimate the impacts and cost-effectiveness of using a package of policy instruments to hit a greenhouse gas target. We focus on a package of three policy instruments that are central to the *Pan Canadian Framework on Climate Change*: a carbon price, a low carbon fuel standard (LCFS), and an electric vehicle mandate (EVM).[18] The level for the carbon price has already been chosen—it will increase to \$50/t CO_2 by 2022. We therefore take this level of carbon tax as given and vary the stringency of the other two policies to hit different abatement goals. Moreover, we choose different relative contributions from the LCFS and EVM in order to this the abatement target. As above, we produce a marginal abatement cost curve to estimate the cost effectiveness

[18] Neither the *Pan-Canadian Framework* nor the more recent Electric Vehicle Strategy Discussion Paper articulate a clear policy for the promotion of electric vehicles. We simulate an EV mandate as a potential form of EV strategy.

of this policy package. It is important to note that except where explicitly mentioned, we do not include existing policies aimed at reducing greenhouse gas emissions from passenger transport in the model, and focus only on new policies.

The following sub-sections provide additional detail on the model implementation of the policies in the model.

4.1 Low carbon fuel standard

A Low Carbon (or Clean) Fuel Standard (LCFS) is a measure aimed at reducing the greenhouse gas intensity of motive fuels by a given proportion. The LCFS is implemented as a tradeable certificates scheme. Producers of fuels with intensity lower than the target intensity earn credits equal to the amount by which they over perform the target. Producers of fuel whose greenhouse gas intensity exceeds the target are required to purchase credits from the producers of the low-carbon fuels.

This is modeled as a combination of an output subsidy on all fuels financed by the revenues from a tax on fuels in proportion to their greenhouse gas emissions. A common LCFS tax is determined, but the rate applied to producers of a given fuel f is scaled relative to the benchmark petroleum-based gasoline as follows:

$$\beta_f = \frac{Z_f L_p}{Z_p L_f}$$

Where Z_f is the life cycle emissions from fuel f and L_f is the labour input into fuel f, and where the subscript p refers to petroleum-based gasoline, which is used as the reference fuel. All ‘revenue’ generated by the tax is used to fund the output subsidies.

4.2 Fuel economy regulations for new vehicles

Fuel economy regulations are implemented in a similar manner to the low carbon fuel standard, based on a certificate trading scheme in the emission intensity of the new fleet of vehicles. This is represented as a combined output subsidy applied to new car driving sectors funded by an input tax applied to fuel use in new cars. The fuel economy regulations do not distinguish between fuels based on their emission intensity. The input tax is applied to the composite of fuels for 'combustion' used in new vehicles only. Since electric vehicles do not use 'fuel' manufacturers generate credits as they increase their sales of electric vehicles. It is important to note that the greenhouse gas intensity regulations simulated in this model differ somewhat from the regulations actually in place in Canada.[19] Most importantly, in-place regulations are size-differentiated, which results in an implicit subsidy for larger vehicles and weakens the effectiveness of the policy. The model used here does not account for vehicle size, and thus likely somewhat overestimates the effectiveness of the fuel economy regulations. Fuel economy regulations are assumed to tighten fuel economy relative to the benchmark data.

4.3 Fuel and carbon taxes

Fuel taxes are applied to all fuels (excluding electricity). Carbon taxes are applied based on the life cycle greenhouse gas emissions of all fuels. The revenue generated is returned to consumers either in lump sum fashion or by reducing overall labour tax enough to bring the government budget balance.

4.4 EV policies

Two types of electric vehicle policies are considered: EV subsidies and an EV mandate. The EV subsidy is targeted to increase the market share of electric vehicles in new vehicle sales. The EV subsidy is provided to the new electric vehicle driving sector. It is financed by a lump-sum tax. That is, the representative household's transfer from Government is reduced by the amount of the subsidies provided. This likely under represents the costliness of the policy if revenue must be generated to finance it.

The EV mandate uses a mechanism similar to the fuel economy regulations. A certificate trading scheme is modeled wherein all non-EV new vehicle driving sectors are taxed with the

[19] For the text of the regulations, see Environment Canada.

revenue financing credits provided to the electric vehicle sector sector.

5 Results

5.1 Individual policies

Figure 3 compares the marginal abatement cost imposed by each of the individual policies that we simulate. Once again, we emphasize that the policies simulated here correspond roughly to a 7-year time horizon, when about half of the vehicle stock is chosen under the new policies, and half is chosen prior to the introduction of the new policies.

For virtually all greenhouse gas abatement targets, the revenue-neutral carbon tax, in which revenue from the carbon tax is used to reduce other tax rates in the economy, is the most cost effective policy. This is an anticipated result, given the structure of our model. Our calculations suggest that to reduce emissions from on-road passenger transportation by about 5 Mt CO_2 per year within five years would require a carbon tax of about \$85/t CO_2. On it's own, the \$50/t tax agreed upon in the *Pan-Canadian Framework* is likely to reduce emissions by 2–3 Mt CO_2 per year. The model suggests that significant emission cuts from on-road transport over a seven-year period would require a high carbon tax. For example, cutting emissions from the sector by 20% over five years would require a carbon tax of over \$400/t CO_2 or more, according to our model (for reference, a \$400/t CO_2 tax would add \$1/L to the price of gasoline).

While the revenue-neutral gasoline gas and carbon tax impose similar costs at modest abatement targets, for more stringent emissions abatement goals, the revenue neutral carbon tax becomes progressively more cost effective. This occurs because it encourages the substitution of low-carbon liquid fuels for gasoline, which is not facilitated by the gasoline tax.

We simulate two variants of the carbon tax and gasoline tax: a revenue-neutral version and a non-revenue-neutral version. The revenue-neutral version uses the revenue from the environmental tax to reduce the pre-existing tax on income. Consistent with other analyses, we find that this approach reduces the cost of achieving an environmental goal. However, both the revenue-neutral and non-revenue-neutral tax policies induce greenhouse gas abatement in a much more cost-effective manner than other individual policies, especially for more stringent environmental targets.

Amongst non-market-based policies, the policies targeting electric vehicles stand out as being particularly costly. Electric vehicle subsidies, in particular, achieve little reduction in greenhouse gas emissions in our model, and do so at a high cost. This outcome occurs because electric vehicle subsidies only affect one margin in the model—providing incentive for consumers to switch from internal combustion to electric vehicles. The narrow base makes this policy approach costly. Moreover, because they subsidize transport activities, they encourage additional transport demand, which works against the main objective of the policy.[20] The EV mandate is somewhat more cost effective than the EV subsidy. This is because the EV mandate functions through manufacturer cross-subsidization of EV vehicles from conventional vehicle margins. By making conventional vehicles more expensive, the EV mandate discourages greenhouse gas emissions from private transport.

The fuel economy standard is nearly as cost effective as the straight gasoline tax and carbon tax at low levels of emission abatement, but rapidly becomes much less cost effective as additional emissions abatement is pursued. This is because the fuel economy standard does not encourage substantial reductions in transport demand, and does little to encourage decarbonization of fuels.

The model suggests that on its own the low carbon fuel standard is substantially less cost effective than the market-based policies that we simulate. As shown in Figure 4, to achieve a 9.1% reduction in annual emissions over seven years, the low carbon fuel standard is dramatically higher than a revenue-neutral carbon tax. One feature of the LCFS is that its MAC curve includes small kinks where blending limits impinge on the ability of low-carbon fuels to reduce emissions further.

Figure 5 helps to explain the differences in the predicted cost effectiveness of different policies. As discussed earlier (see Equation (1) and related text), it is possible to decompose the change in per capita emissions from on-road travel into four components, in order to highlight the four key

[20]It is important to note that our model does not include all features of the electric vehicle market, and some of these omissions could be important in evaluating EV policies. For example, we do not model electric vehicle charging infrastructure, which is likely to generate network effects. We also do not attempt to model any consumer or manufacturer learning associated with electric vehicle adoption. Both of these omissions would make EV subsidies more cost effective than we estimate here, although they would likely remain expensive relative to other options.

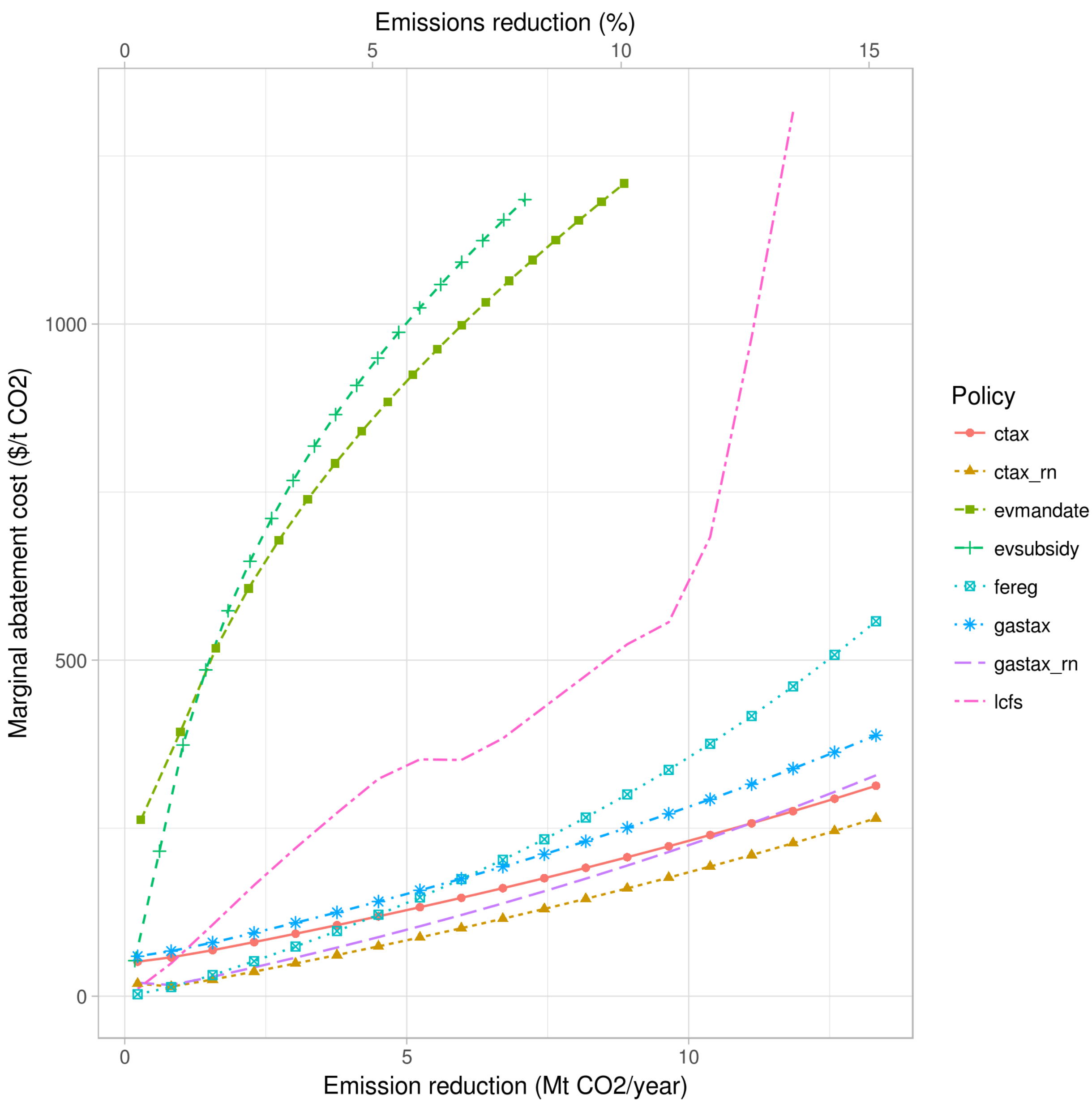

Figure 3: Marginal abatement curve for individual policies. The marginal abatement curves reflect a medium-run (roughly 7 year) time horizon.

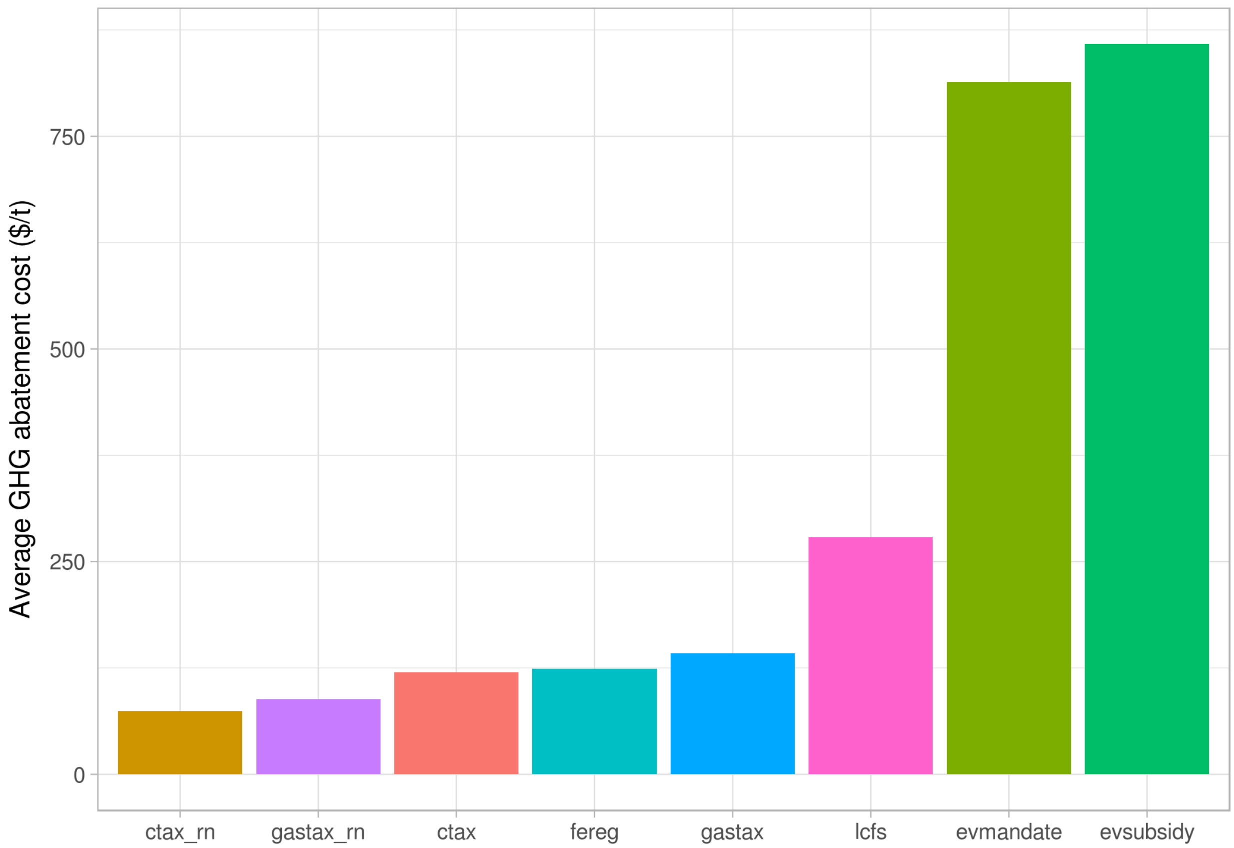

Figure 4: Average cost of greenhouse gas abatement imposed by individual policies. Each individual policy reduces greenhouse gas emissions from the transport sector by 9.1%. Average cost is calculated as the change in consumer welfare (equivalent variation in income) divided by the change in greenhouse gas emissions.

actions that can reduce emissions: reducing overall travel demand, switching modes, improving fuel efficiency, and decarbonizing fuels. Figure 5 shows how each of the policies simulated generate greenhouse gas reductions via each of these activities. It is useful to compare policies to the carbon tax, which as described in section 2.2 produces the cost-effective distribution of emission reductions from across the four actions.

The carbon tax causes a small reduction in overall passenger transport demand of about 0.6%. It also causes a small shift towards public transport and away from private vehicles, which reduces greenhouse gas emissions. It causes a substantial improvement in vehicle fuel economy, of about 12%. Finally, it reduces the greenhouse gas intensity of fuels by 0.8%.

There is a notable difference in the sources of greenhouse gas reductions for other policies. The gas/fuel tax does not differentiate between liquid fuels, and so causes less improvement of the emissions intensity of the fuel supply than the carbon tax. As a result, it must achieve slightly more greenhouse gas reductions from other channels—at higher cost—than the carbon tax. The fuel economy regulations do not provide incentives for consumers to drive less or to switch modes, nor do they provide incentives for reducing the emissions intensity of fuel supply. As a result, they must achieve all GHG reductions via improvements in fuel economy, which are significant at over 20%. In contrast, the low carbon fuel standard does not provide substantial incentives for improvements in fuel economy, and as a result much achieve much more emission reductions via decarbonization of the fuel supply.

5.1.1 Sensitivity Analysis

We present the results of a sensitivity analysis in Figure 6. In this figure, we focus on three key policies that are central to the *Pan-Canadian Framework*: the (revenue-neutral) carbon tax, the low carbon fuel standard, and the electric vehicle mandate. Similar to the prior section, we develop a marginal abatement cost curve for each of these policies. However, in this section, we present runs from our seven sensitivity "cases" as well as our central case (labelled CC). The sensitivity cases were chosen to highlight how the model responds to changes in key parameters.

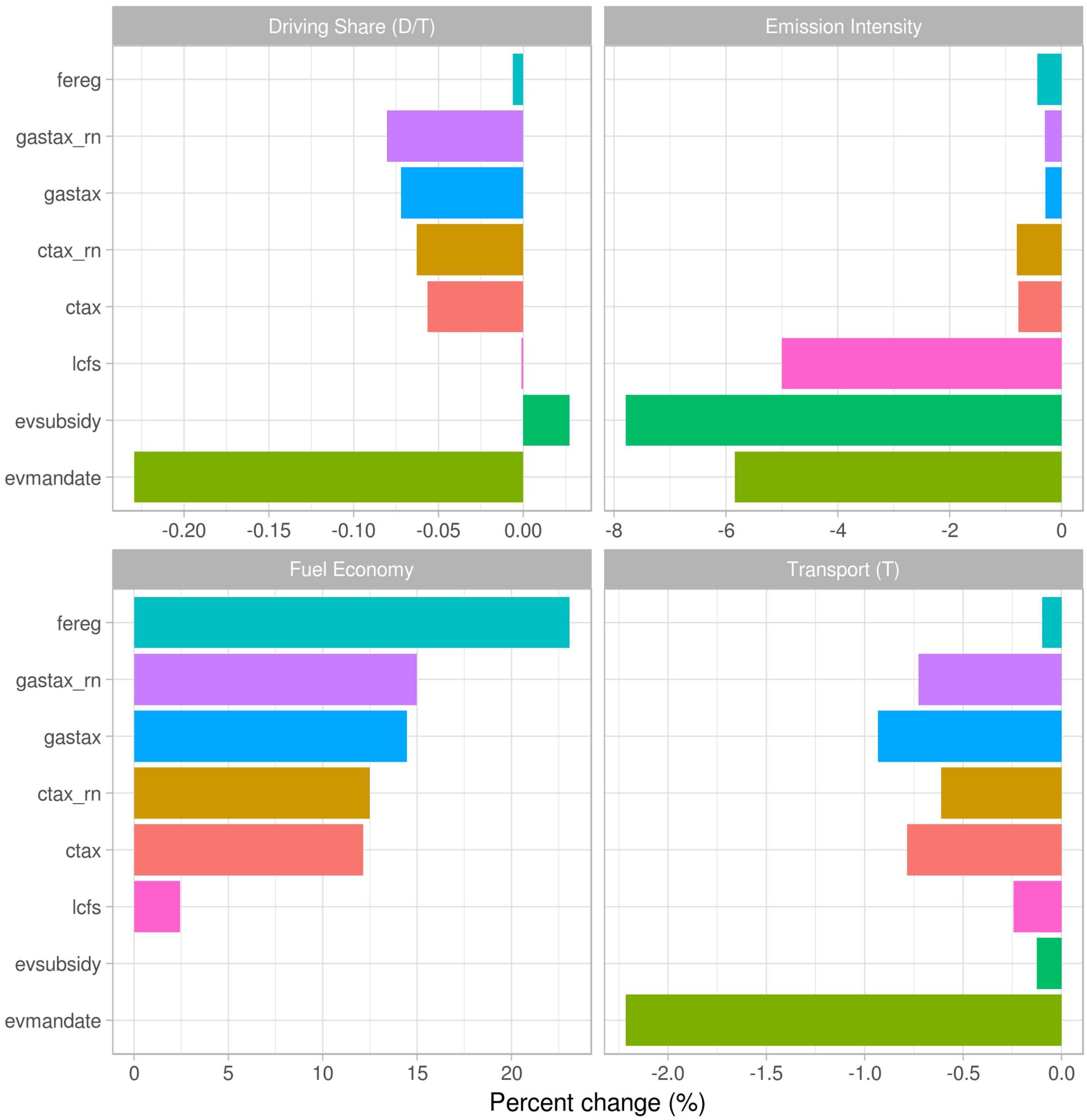

Figure 5: Decarbonization Activities. Greenhouse gas emissions from on-road passenger transport can be reduced by reducing overall transport demand, reducing the share of overall transport demand supplied by private vehicles, improving vehicle fuel economy, or reducing emission intensity. The figure highlights how each pathway serves to reduce emissions under the policies simulated. Each policy reduces greenhouse gas emissions from on-road passenger transport by about 8 Mt/year.

We conducted limited sensitivity analysis for the following cases:

HEF 50% higher elasticity of substitution between transit (P) and driving (D) as well as between fuel and other inputs in all driving sectors

HFF 50% higher elasticity of substitution among fossil fuel intrinsic composites, that is substitution between gasoline, ethanol, diesel, natural gas and propane

HFX 50% higher elasticities of substitution between a sector's fuel composite and other inputs.

LBL Looser Blend Limits: restrictions on blending of ethanol and biodiesel are relaxed by 50% relative to the central case

LCN LCFS excludes electricity — the LCFS covers only liquid and gaseous fuels

LEB lower emission profiles and unit costs for biofuels relative to our central case

VLE very low emission profiles: this case reflects rapid best-case scenarios for emission reductions.

For further detail on our sensitivity cases with respect to renewable fuels, see Appendix section B and Appendix table 7.

The costs of policies we model are—not surprisingly—sensitive to model parameterization. The main immediate observation is that for the domain of our sensitivity analysis, the MAC curves for the EV mandate and carbon tax are rather compact. This contrasts with the curve for the LCFS, which is shifted markedly by many of the parameter changes. For a reduction target of 10 Mt, the MAC is under \$325/t in case VLE, but over \$825/t in case (LCN) where the LCFS covers only liquid and gaseous fuels (excluding electricity). The VLE sensitivity case relates to the costliness and emission intensity of renewable fuels. For the entire range of parameters considered the revenue-neutral carbon tax remains the most cost-effective than any of the individual regulatory options.

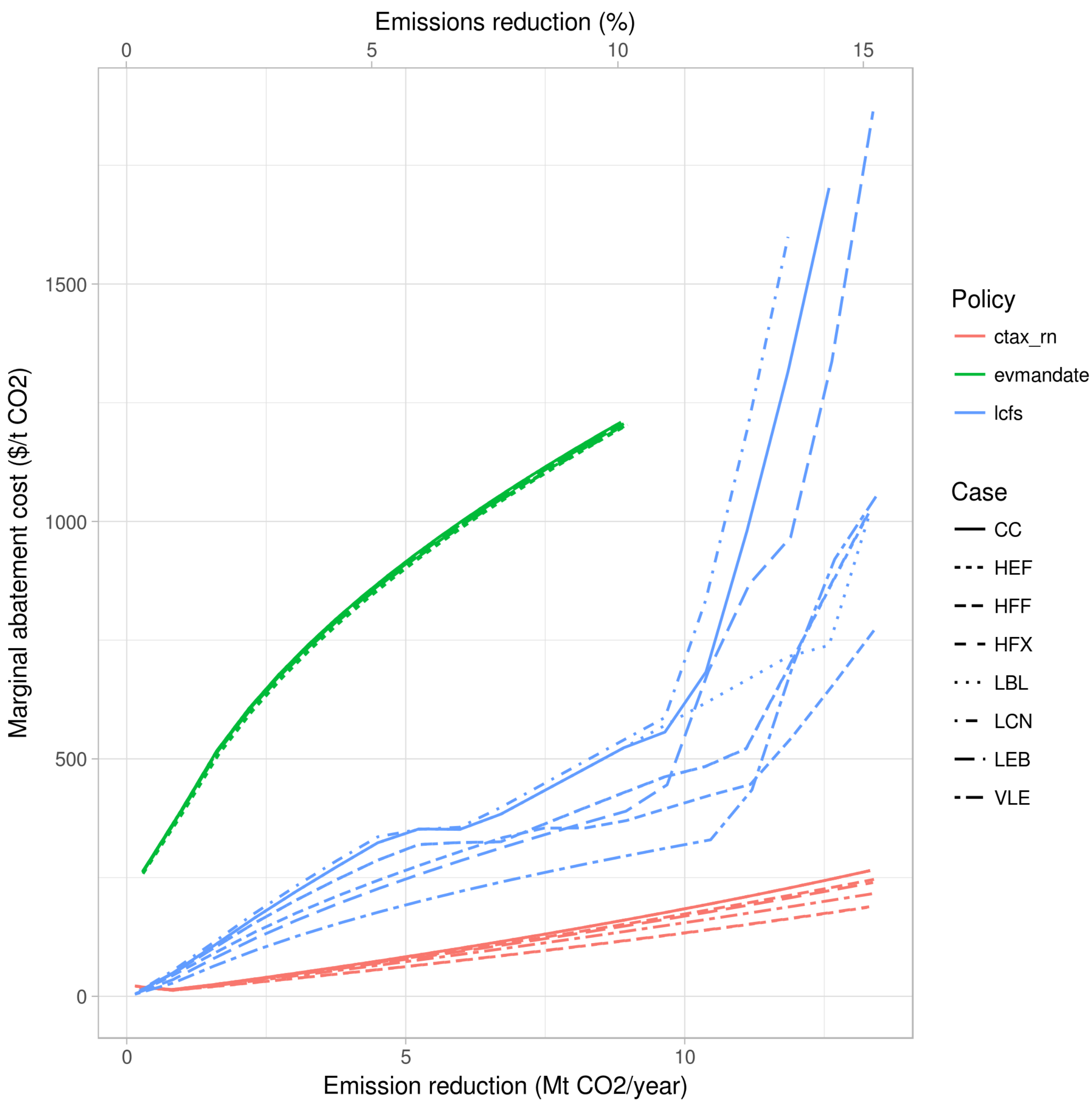

Figure 6: Marginal abatement curve sensitivity analysis

6 What Mix of Policies?

The prior section simulated a number of individual transport policies, and showed that carbon taxes are able to reduce transport sector emissions at substantially lower cost than individual regulatory policies. In practice, however, policy makers do not typically implement a single regulation to reduce emissions, but instead use a number of regulations concurrently. This is the approach taken by the *Pan-Canadian Framework*, which proposes a carbon price, clean fuel standard, and electric vehicle strategy on top of a carbon price as well as previously implemented regulations governing the greenhouse gas intensity of new vehicles. In this section, we focus on (1) how to optimally choose this combination of policies—in particular the two policies currently being designed, and (2) the cost-effectiveness of the package of policies. In each case, these policies are modeled as additional to the already-committed carbon price benchmark of $50/t (in 2022) and fuel economy regulations which are assumed to improve the fuel economy of the vehicle fleet by 5%. In our model these together are enough to reduce transport sector emissions by 5.7%. Our policy baseline includes 1. removal of all existing supports for biofuels, 2. a $50/t carbon tax, and 3. 5% tightening of fuel economy regulations.

To simplify the issue, we focus specifically on an EV mandate as described earlier since most economic analyses favour the EV mandate over EV subsidies. We consider combinations of EV mandate and LCFS policies that achieve 1–13% further emission reductions than our policy baseline. This amounts to reductions from our benchmark case (before the reductions brought about by the carbon tax and fuel economy regulations) of 6.5–18%.

6.1 Methodology

For each emission reduction target from 1% to 16% relative to the policy baseline, we first fix a target market share for new sales of EVs between 1 and 13 times the policy baseline level of approximately 1.3%.[21] With this policy in place we determine the tightness of LCFS needed to hit

[21] Because the policy baseline is itself generated by our model, the results of the baseline policy lead to slightly different levels of EV penetration under different parameter configurations.

the given target. In each case, the carbon tax, fuel economy regulations and EV share are fixed, with the LCFS endogenously selected to hit the emission reduction target. For each target we evaluate each 'mix' of EV mandate and LCFS and select the one with the lowest cost. The same procedure is used for each of our parameter configurations.

6.2 Findings

Figure 7 shows the EV targets and LCFS shares associated with our central case parameter configuration. The EV target defines the target share of EVs in new vehicle sales. A value of zero means that an EV mandate is not part of the loss-minimizing policy. Any positive value shows the ratio of new EV sales to total new vehicle sales. The first point on the curve represents the policy combination for a target reduction of 1%, with each subsequent point representing a further 1% reduction. The end points represent the policy combination associated with a point on the curve correspond to a 16% reduction of passenger road transportation emissions. In findings not shown in the paper, the same reduction is achieved in the VLE case with an EV target of 11.8% and an LCFS of 13.8%. See Appendix Table 10.

Before modeling the policies together, the MAC curves would have suggested that the EV mandate would play no role in the optimal (loss-minimizing) policy mix. This turns out not to be the case in any of our parameter configurations. As many authors have mentioned[22] there are many interactions among these policy instruments. In the case of an LCFS and EV Mandate, the LCFS will cause an increase in the price of fuel. Initially the increase is modest, but as the LCFS target gets larger, the cost rises due in part to limitations posed by the existing stock of vehicles. As the cost of fuel goes up, it becomes easier to convince drivers to adopt EVs. Evidence cited earlier suggests that purchasers of new cars are relatively responsive to changes in the relative cost of driving alternative vehicles. This seems to be the key interaction at work in our findings.

In all configurations the welfare cost of reducing emissions an added 10% relative to the policy baseline is approximately 3–4 times as costly as reducing the emissions by 5%.[23]

[22](McGuinness and Ellerman, 2008; Böhringer and Rosendahl, 2010; Fischer, 2010; Levinson, 2010)

[23]The cost of the 5% reduction is approximately 1 $B while the cost of reducing passenger road transport emissions

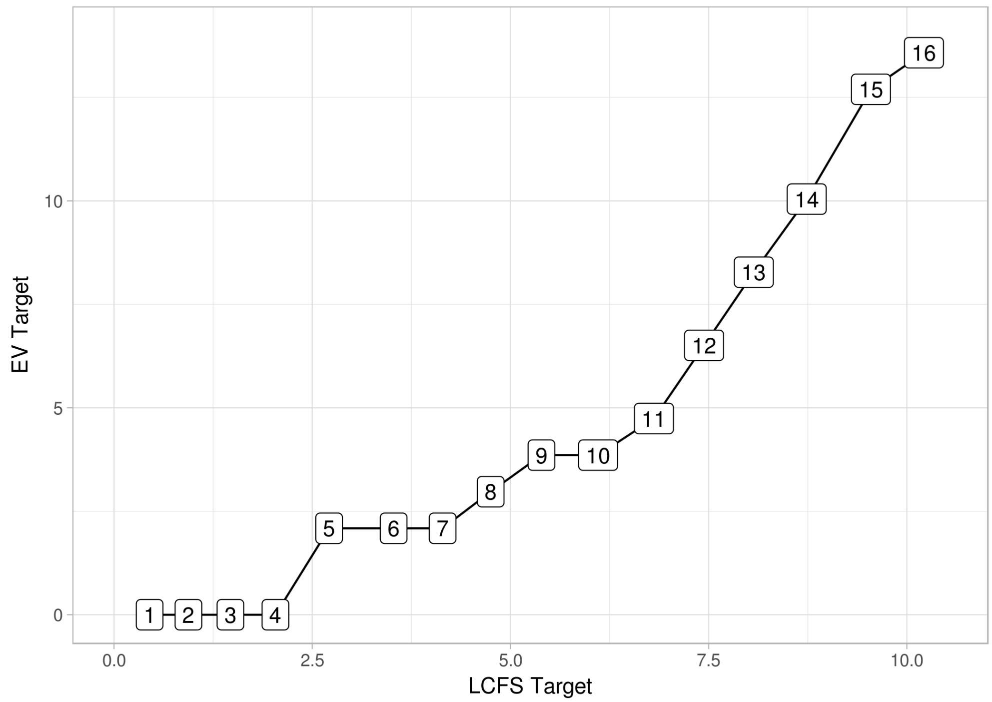

Figure 7: Loss-minimizing combinations of EV target share and LCFS share. The label indicates percentage reduction in emissions, from 1 to 16% beyond emission reductions induced by the carbon price and vehicle greenhouse gas intensity regulations. The EV target is the percentage of new vehicle sales required to be electric. The LCFS target is the percentage reduction in the greenhouse gas intensity of vehicle fuels required by the clean fuel standard.

6.3 Marginal Abatement Costs Reconsidered

Figure 8 shows the central case MAC curves for all the instruments we considered above plus our optimally chosen policy package. This figure first illustrates that the lowest-cost policy package has a significantly higher marginal abatement cost than a revenue neutral carbon tax. For 7 Mt reduction in emissions (a reduction of 8% relative to the policy baseline[24]) the marginal cost of a revenue-neutral carbon tax is $130, whereas the marginal cost of an LCFS is $430. The EV mandate on its own struggles to achieve this reduction, with the marginal abatement cost reaching $1,125.

It also illustrates that the lowest-cost policy package yields a much lower marginal abatement

by 10% is near $3B in all cases.

[24]This reduction approximately corresponds to the initial target of 10 Mt discussed in earlier sections since this reduction is relative to the policy baseline.

cost than either the LCFS or the EV mandate individually. This amounts to taking advantage of the low-cost segments of the two MAC curves. Although the optimal policy package remains more costly than the revenue-neutral carbon tax, our analysis suggests that the typical economic comparison of individual instruments is somewhat misleading. In practice, a well-chosen combination of regulatory policies can yield a cost-effectiveness that does not depart significantly from that of a carbon tax. It is important to note that this conclusion relies on policy-makers being able to optimally select the combination of regulatory policies. As Figure 7 shows, the optimal combination of polices (in our model) is strongly dependent on uncertain parameters, so choosing the best combination is likely to be difficult.

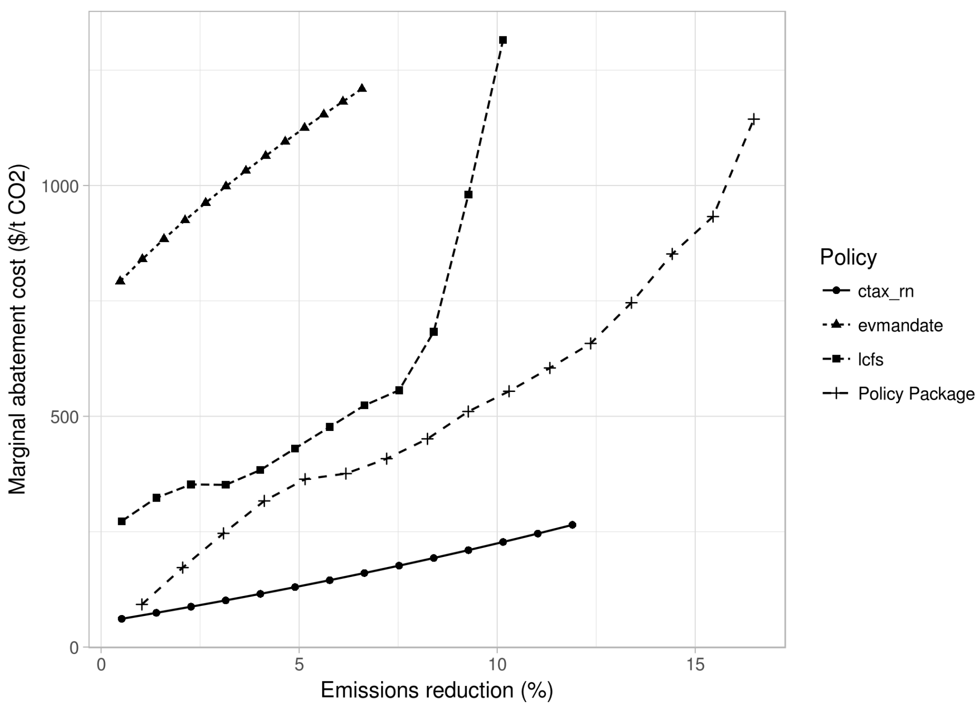

Figure 8: MAC Curves: Single Policies and Recommended Policy Package

7 Conclusions

The reduction of greenhouse gas emissions from road transport is a key policy goal. This paper has considered reducing emissions from road passenger travel in Canada. While numerous other studies have considered marginal abatement cost (MAC) curves for various policies, this paper focuses more on a particular dimension of policy choice, that is choice of the relative stringency of a federal EV mandate and federal LCFS standard *given* announced fuel economy regulations and a carbon tax.

Like most others we find that the carbon tax has the lowest marginal abatement cost of all instruments, meaning that using a carbon tax on its own would minimize the social cost of a given emissions reduction goal. This is in part because the carbon tax gives appropriate incentives at all the relevant margins, whereas the other instruments do not. We also find that individual regulatory instruments, such as a low carbon fuel standard, zero emission vehicle mandate, or fuel economy regulation, are costly to achieve substantial emission reductions. However, when we simulate a combination of regulatory instruments—such as being considered by governments in Canada currently—we find that it is possible for the cost-effectiveness of a regulatory approach to be substantially improved. This conclusion requires judicious choice of policies to combine. Our research suggests that a low carbon fuel standard plus a relatively weak zero emission vehicle mandate would be an appropriate policy combination in Canada.

A simple intuition helps understand our finding that a blend of LCFS and EV mandate lowers cost relative to using one alone. This is the fact that by using both instruments together we exploit the low-cost segments of each MAC curve. Because of our focus on the near term (next 5 years) the LCFS MAC curve eventually gets quite high as a result of the constraints imposed by the existing vehicle fleet which for the most part is unable to use higher-ratio blends of some renewable fuels. Likewise, resistance to EV adoption is in part due to concerns about the sparseness of the charging network. Using both instruments together results from more than just taking advantage of low cost portions of the MAC curve, since the LCFS and EV mandate interact. As the share of EVs expands, the cost of satisfying a given LCFS standard falls, because less of the higher cost low-carbon fuels need to be produced. Likewise as the LCFS standard is raised, the cost of fuel for internal-combustion cars rises, making it easier to convince drivers to purchase an EV.

There are many qualifications to our findings. As with any simulation study of this type, our results depend on a number of parameters, some of whose values are not estimated or on which there does not exist a consensus. We also do not address two additional issues relevant to policy choice. Our model also does not allow us to assess distributional impacts since we only have one representative consumer. Having said that, it seems likely that distributional concerns would work in favour of the LCFS at the expense of the EV mandate since higher income households tend to be more likely to buy EVs.

A further consideration is the argument that support for EVs is about enabling a significant transition from fossil-fuel powered vehicles to electric vehicles. The argument is that providing adequate supports will give market incentives for better infrastructure (charging stations in particular). Finally we do not represent the added benefits resulting from a move to more EVs, the reduction in local air pollutants. Moving to electric vehicles from even low-carbon fuels is likely to reduce local air pollution further. The benefits from such local air quality improvements can easily outweigh the benefits from reducing greenhouse gas emissions.

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A Substitution Parameters

Our key model parameters for the central case runs are listed in Table 5. This is followed by Table 6 with detail on the elasticities of fuel–other input substitution by vehicle class and for transit.

Parameter	Symbol	Value
Substitution between transportation and other goods	σ_C	1.3
Substitution between transit and driving	σ_T	0.2
Base substitution elasticity between fuel composites and other inputs in driving and transit[a]	$\overline{\sigma}_D$	0.2
Substitution among driving (vehicle) classes	σ_V	9.0
Substitution among fossil fuels[b]	σ_F^v	4.0
Substitution between electricity and fuel composite[c]	σ_{ef}	1.0
Substitution among individual fuels in intermediate composites[d]	σ_f^G	8.0
Substitution between existing vehicles and other inputs[e]	σ_{XV}	0.1

[a]See detailed discussion below page 25.

[b]This parameter concerns substitution among the 'intermediate' fossil fuel composites. v ranges over the vehicle classes and transit.

[c]This parameter is relevant for transit only

[d]This parameter is applicable only to diesel and ethanol.

[e]This is relevant for extant vehicle sector only.

Table 5: Central Case Parameter Configuration: Key Parameters

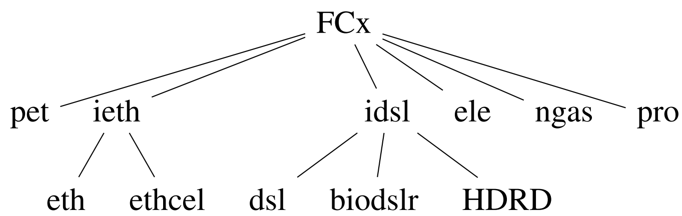
	Factor[a]	CC[b]	HFX[c]
Transit	0.70	0.45	0.68
Existing Fleet	0.30	0.19	0.29
New Internal Combustion	1.00	0.65	0.97
New Hybrid	0.30	0.19	0.29
New Electric Vehicle	0.10	0.06	0.10

[a]factors to scale substitution parameters between fuel composites and other inputs

[b]all cases except HFX

[c]sensitivity case with higher (easier) substitution between fuel composite and other inputs

Table 6: Substitution Between Fuel and Other Inputs by Vehicle Class



FCC fuel composite for combustion private vehicles — includes all fuels; gasoline dominates

FCT fuel composite for public transit — includes all fuels; diesel dominates

FCE fuel 'composite' for all-electric vehicles only — only electricity is included

ieth, idsl the 'intermediate' composites

Figure 9: Tree Representation of Fuel Composites

B Vehicle and Fuel–Related Input Data

Table 4 Provides an overview of the data we used to populate our driving sectors by vehicle class and transit. Table 7 provides key details of the unit costs and emissions profiles of renewable fuels.

Because our aggregation of fuels (see table 2) differed from some of our sources it was necessary to patch together data on emission factors and unit costs from different sources.

In our central case, the emissions factors were first sourced from Ministry of Mines and Energy (2014). This data did not include emission coefficient for cellulosic ethanol. It was sourced from Vass and Jaccard (2017) using the mean of their range. For the LEB case, the mean value of emission coefficients for petroleum, ethanol, biodiesel, cellulosic ethanol and HRD from Vass and Jaccard (2017) were used. For the VLE case, the 'maximum reduction' emission coefficients for petroleum, ethanol, biodiesel, cellulosic ethanol and HRD from Vass and Jaccard (2017) were used. The emissions coefficients for all remaining fuels are those in Ministry of Mines and Energy (2014).

Four our central case unit costs we used Cazzola et al. (2013) under the $60/barrel scenario. This provided values for all of our fuels except HDRD. Our unit cost figure for HDRD is from Moorhouse (2017).

For both of the alternative cases (LEB and VLE) the unit costs for renewable ethanol and biodiesel were assigned the values from (Vass and Jaccard, 2017)[25]. Prices for all other fuels were sourced from Cazzola et al. (2013).

	Emission Factors (g/MJ)		
	CC	LEB	VLE
Gasoline from petroleum	87.00	87.00	87.00
Diesel from petroleum	90.01	90.01	90.01
Ethanol (most from corn)	51.22	26.53	13.05
Cellulosic ethanol	18.70	18.70	6.96
Biodiesel from rapeseed/canola	21.47	10.44	7.83
Hydrogenation Derived Renewable Diesel	43.80	19.58	13.92
Propane	75.50	75.50	75.50
Natural Gas	57.61	57.61	57.61
Electricity	11.52	11.52	11.52
	Cost ($ per litre equiv)		
	CC	LEB	VLE
Gasoline from petroleum	1.12	1.12	1.12
Diesel from petroleum	1.04	1.04	1.04
Ethanol (most from corn)	1.81	1.62	1.62
Cellulosic ethanol	2.19	2.00	2.00
Biodiesel from rapeseed/canola	1.93	1.67	1.67
Hydrogenation Derived Renewable Diesel	1.81	1.87	1.87
Propane	2.18	2.18	2.18
Natural Gas	0.75	0.75	0.75
Electricity	0.64	0.64	0.64

Table 7: Sensitivity Cases: Emission and Costs of Biofuels

C Policy Mix Sensitivity

Figure 10 provides sensitivity analysis of the optimal policy mix. The lines corresponding to each case have different end points because it takes different combinations of EV mandate and LCFS to achieve a given emissions reduction target with different parameter configurations. Each point is indicated by the percent emissions reduction (beyond the policy baseline) that is achieved. The parameter configurations yield different responses from the two policy instruments, so for example,

[25] Current retail price diesel+nat gas

an EV target of 4% combined with an LCFS target of 15% is enough to reduce emissions by 10% in the central case (CC).

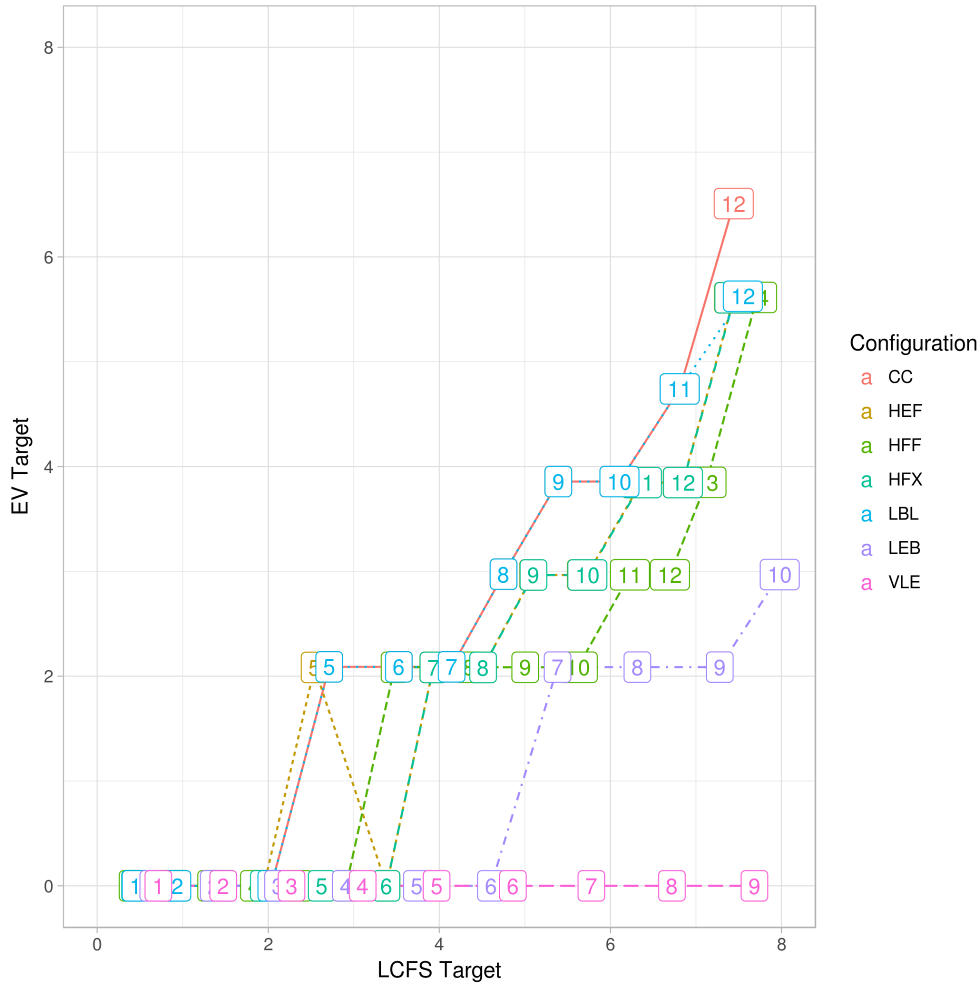


Figure 10: Loss-minimizing policy combinations