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The Economic Case for EV Supports? Or: Network Effects, EV Pessimism and EV Supports

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Preliminary — Please Do Not Cite

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*The author acknowledges comments from participants at the 2018 ONSEP meeting in Prince Edward County. Remaining errors are my own. e-mail: `rwigle@wlu.ca`

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1 Introduction

Key Citations: Zhang and Dou (2019); Gillingham et al. (2019) Hardman et al. (2018)

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]

The Canadian government is currently considering ways to regulate GHG emissions from on road transport, focusing in particular on the low carbon fuel standard (LCFS) and ways to support the purchase of zero-emission vehicles, notably electric vehicles (EV)s. This paper reconsiders the cost effectiveness of these two instruments in the context of a model incorporating two features absent from earlier research on the economics of policies to reduce on road transport GHG emissions in Canada: network effects, and 'EV pessimism.' We use the term EV pessimism to refer to the overestimation by buyers of the overall cost of driving an EV. This can include several elements: 1. overestimation of the cost of an EV with the desired range and features, 2. overestimation of the costs and inconvenience associated with driving an EV including range anxiety.

Our particular extension of this work is to investgate the range of parameters for which EV Mandates become cost-effective. The current findings suggest that rather strong impacts would be needed to make an EV mandate cost effective. but we have little evidence about the strength of these effects on which to make a judgement. The results of the exercise should thus be treated as indicative at best, since not only the strength of the effects nor the functional representation of either mechanism are speculative. Having said this, our preliminary work suggests that modeling EV pessimism in particular changes the quantitative evaluation of EV supports sometimes significantly, but the main result of earlier analysis (that EV supports are likely to be costlier ways to achieve large reductions of GHG emissions) is only likely to be overturned with rather strong effects.

2 Literature

Most economic analysis of EV supports in Canada have found them to be very high cost approaches to reducing GHG emissions relative to a carbon tax in particular, but even relative to other approaches to reduce GHG emissions from transport alone.

[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.

2.1 Policy Background: EV Supports

While many GHG-related policies such as carbon taxes, or fuel economy regulations may have the indirect effect of making EVs more attractive, direct support for EVs comes in a number of forms: 1. EV purchase subsidies, 2. EV mandates, 3. subsidies to public charging stations, and 4. subsidies to purchases of home charging stations. Canadian federal and provincial governments have in the past supported EV purchase through subsidies although at this point only the federal government, Québec and British Columbia continue to provide subsidies for EV purchase. Federal Budget 2019 charges Transport Canada with negotiating with auto manufacturers to achieve voluntary EV sales targets (as opposed to a mandate). The Budget also includes $130M over 5 years for supporting the public EV charging stations.

The only active support for home EV charging stations are the Québec provincial plan and small supports from a handful of Québec municipalities. Sherbrooke, the largest of the communities[2] offers a $500 subsidy for the purchase and installation of a home Level 2 station. Other community supports range between $100 and $500. British Columbia has a program whose budget has been spent but which could be restarted.

2.2 EV Mandates and EV Subsidies in Canada

A number of papers argue that EV supports either via an EV mandate or through EV subsidies are likely to be very high cost or worse could actually increase emissions.

Rivers and Wigle (2018a,b) argue first that both an EV mandate and EV subsidies fair poorly against all other instruments considered to reduce road transportation emissions. These papers were written in the context of considering the role of EV supports and a low carbon fuel standard (LCFS) in the policy mix for reducing road transportation GHG emissions. The other instruments considered include carbon taxes, tightened fuel economy regulations, and fuel taxes. The EV mandate fared better than the EV subsidy since it gives incentives to reduce the purchase of new IC vehicles as well as promoting EV sales, whereas the EV subsidy provides only the latter incentive. To reduce GHG emissions by 8 Mt, these papers argue that the marginal cost of doing so by an EV mandate (or subsidy) would be over $1,100/t whereas the same target could be achieved at marginal costs in the range of $130–235/t for carbon taxes, fuel taxes or fuel economy regulation. The LCFS occupied the middle ground with a marginal cost of $430/t.

Loveys (2017) argues that 'the economists are wrong' about consumer subsidies for EV purchases. First, existing analysis ignore the fact that new technologies take a long time to become widely used, suggesting that there need to be subsidies for a long time for them to succeed. The second argument is that EVs constitute the only viable way to reduce GHG emissions in Canada. Finally, the article argues that rapid emissions reductions are required, which are only achievable through consumer subsidies to.

2.3 Québec's Drive Electric Program

Mercier et al. (2015) conduct a benefit-cost analysis of Québec's Drive Electric Program and conclude that it has a positive net value. The costs of the program are assumed to be the costs of administering the program, whereas the benefits include fuel savings, reduced service costs and emission reductions. Barla (2018) notes that their calculated cost does not include the higher cost of electric vehicles relative to their IC counterparts.

[2] Population of 160,000.

Irvine (2017) focuses on how EV supports interact with existing fuel economy regulations. Because Québec's Québec's Drive Electric Program specified a fixed target share of EVs in new vehicle purchases, the paper argues that it is even possible that the higher share of EVs resulting from the program could 'room' created by the program could allow more high-emitting vehicles to be purchased, effectively relaxing the federal fuel economy regulations. The overall effect on emissions would be unclear.

3 Economic Analysis of EV Supports

As a general observation, economic analysis has not supported EV subsidies as a cost-effective approach. This is based in part on the observation that they target only one dimension of decision making related to road transportation emissions. They directly influence the new-vehicle purchase decision between EVs and IC vehicles, but without affecting a number of other relevant decisions. Travellers must also decide about 1. mode choice between transit and driving, 2. distances travelled, 3. fuel choice between more or less-carbon intensive fuels.

Existing work that we are aware of does not consider two other issues which we model here:

network effects When the auto fleet includes very few EVs, there tend to be correspondingly few charging stations making it harder for drivers to plan long trips in an EV. Expanding the number of charging stations will reduce this problem. Likewise, services aimed at EV drivers, including service centres with mechanics trained to service EVs are less common.

EV pessimism Because driving an EV is somewhat novel, it is possible buyers overestimate the overall cost of driving an EV when new vehicle purchase decisions are made. This overall cost will include an allowance for inconvenience from range limitations of the vehicle or concern that the vehicle may not be serviceable in all locations. They may not appreciate how much they will save on fuel and maintenance. If this is indeed the case, a policy which increases the adoption of EVs could be efficient to the extent it offsets these incorrect expectations.

4 Modeling Issues

For this paper, we modify the model used in our earlier papers to allow for network externalities and EV pessimism. A description of the remaining elements of the base model is provided as Appendix A.

4.1 Network Externalities

Metcalfe's law states that the 'utility' of a network is asymptotically proportional to the square of the number of nodes.[3] To the extent that increases in the number of EV charging stations increases this network effect, we would expect the overall cost of driving an EV to fall. We do not explain the expansion of the number of charging stations (nodes), but rather assume that they arise endogenously from having a larger market for their services. Likewise we are unaware of estimates that would link the value of an EV charging/servicing network to the number of EVs. Nonetheless we proceed with some assumed parameters to investigate the size of such effects that would be necessary to significantly change the analysis of EV supports in Canada.

[3] The number of unique connections possible in the network with n nodes is $n(n-1)/2$ which is asymptotically proportional to n^2. `https://en.wikipedia.org/wiki/Metcalfe%27s_law`Wikipedia page on Metcalfe's Law.

Expanding a network by adding nodes increases its value to members of the network of charging stations and other services but we are unaware of any estimate of the aggregate benefits from such expansion.[4].

We adopt a formulation commonly used for modelling learning externalities whereby a parameter ξ is chosen to calibrate to a cost saving from learning associated with doubling the historical output of the good subject to learning externalities. In the case of network externalities we choose ξ to reproduce hypothesized network effects associated not with doubling the size of the network, but rather with doubling the number of EV sales.

$$\gamma = \left(\frac{Y}{\bar{Y}}\right)^{\xi}$$

where

$$\xi = log(1-\phi)/log(2)$$

Symbol	Description
ξ	network externality exponent
ϕ	proportional externality rate[a]

[a]A 5% cost reduction from doubling the number of EVs in the fleet implies $\phi = 0.05$

Table 1: Network Effects

This formulation is speculative in two respects. First it relates the cost-reducing of expanding the *network* to the number of new vehicles purchased as opposed to the number of nodes in the network. Further, we have no estimates on which to base the choice of ϕ.

4.2 EV Pessimism

Because of the lack of experience with EVs, it's possible that those making a new vehicle decision assume that the overall cost of driving an EV to be much higher than it is in reality. We include in this cost concerns about range and lack of charging points as well as concerns that the vehicle will not be readily serviceable in the case of a break down. There can also be concerns about the durability and replacement cost of batteries. We assume then that when making the vehicle purchase decision, buyers proceed as if the cost of driving an EV is unrealistically high.

To clarify, the true cost we are considering is the cost of owning and operating the EV. This includes purchase, service, recharging, insurance and all other costs associated with operating the vehicle.

This error in cost estimates is modeled as a 'tax' on driving electric vehicles. The proceeds of this tax are recycled back to consumers, thereby nullifying any income effects from the tax. Denoting the price on which vehicle choice as π_E^D, a tax of τ_E is applied to driving EVs.

$$\pi_E^D = (1+\tau_E)P_E^D$$

[4]There is some analysis about the value of a network which is rather abstract at this time. An example is Dragicevic (2017). There is also work on the optimal number of nodes in an EV charging network He et al. (2014); Adler et al. (2016); Huang et al. (2015); Farahani et al. (2013). In small dimensional networks the optimal number of charging stations is achieved relatively quickly, but it is hard to generalize this insight because of computational challenges.

4.3 Configurations Considered

Our central case (CC) configuration features neither network externalities not incorrect cost estimates and uses the central case substitution parameters from Rivers and Wigle (2018b). That is to say τ_E and ϕ are both zero. We also consider the following cases:[5]

NN No network effect or EV Pessimism[6]

NNE No Network 10% EV Pessimism

NNEE No Network 20% EV Pessimism

SN CC but 10% network effect

SNE CC but 10% network effect and 10% EV Pessimism

SNEE CC but 10% network effect and 20% EV Pessimism

USN CC but 15% network effect

USNE CC but 15% network effect and 10% EV Pessimism

USNEE CC but 15% network effect and 20% EV Pessimism

5 Experiments

We consider EV supports using an EV mandate approach. The EV mandate operates by subsidizing the EV driving activity while taxing the drivers of new IC vehicles. The tax and subsidy are chosen to be self-financing. In other words the tax revenue from the 'IC tax' equals the subsidies provided to EV drivers. By changing the target share of EVs in new vehicle purchases, larger reductions in GHGs can be attained.

We focus on how the evaluation of an EV mandate changes in the presence of network effects and cost overestimates. In particular we ask:

1. how the EV mandate performs relative to other policy instruments available, and
2. how large should the role of the EV mandate be relative to an LCFS.

The first question is answered by deriving marginal abatement cost curves for four policy instruments:

EV mandate Sales of new vehicles are required to include a specified share of EVs. Vehicle manufacturers are likely to subsidize sales of EVs while charging more for internal combustion (IC) vehicles.

carbon tax a revenue neutral tax on GHG emissions from road transport — Income taxes are reduced so that government revenue remains the same.

LCFS low carbon fuel standard — vehicle fuels are taxed or subsidized relative to their GHG content in such a way that the revenue from taxes on high-carbon fuels finances the subsidies to low-carbon fuels.

[5] In all these cases, the remaining substitution parameters remain at central case values.

[6] This corresponds to the Central Case in Rivers and Wigle (2018a,b).

fuel economy regulation Average fuel economy of new vehicles is regulated via a tradeable allowance scheme.

These findings are discussed in Section 6.

To answer the second question, we first compute a policy baseline of carbon taxes and fuel economy regulations that have already been committed to for the next 5 years. We then compute the social cost of all alternative combinations of LCFS and EV mandate to achieve various emission reductions targets. Finally we choose the combination of EV mandate and LCFS that minimizes social cost for a given emission reduction target. These findings are discussed in Section 7.

6 Cost Effectiveness

Figure 1 shows the marginal abatement cost curves for the selected policy instruments for the case where there are neither network effects nor EV pessimism. It illustrates some key messages relating to cost-effectiveness from Rivers and Wigle (2018b), notably:

1. The revenue-neutral carbon tax is cost-effective for all reduction targets considered. This is primarily because the carbon tax gives incentives to reduce emissions at all of the margins where drivers make decisions.

2. Fuel economy regulation is somewhat less cost-effective. While it still only affects new-vehicle purchases, the regulations give direct incentives to purchase less-emissions intensive vehicles and direct incentives to purchase more non-polluting vehicles such as EVs.

3. Both the LCFS and EV mandate are very high cost. In each case, the policies have their direct impacts through a limited number of decisions. In the case of the LCFS this is the emissions intensity of fuels, and in the case of the EV mandate this is only the decision between EVs and IC vehicles.[7]

4. The LCFS is always more cost-effective than the EV mandate. The direct effect of the LCFS is to give incentives to use less emissions-intensive fuels but because these fuels are more expensive, there is also incentive to reduce driving and purchase a more fuel-efficient vehicle. By contrast the EV mandate works through just one channel.

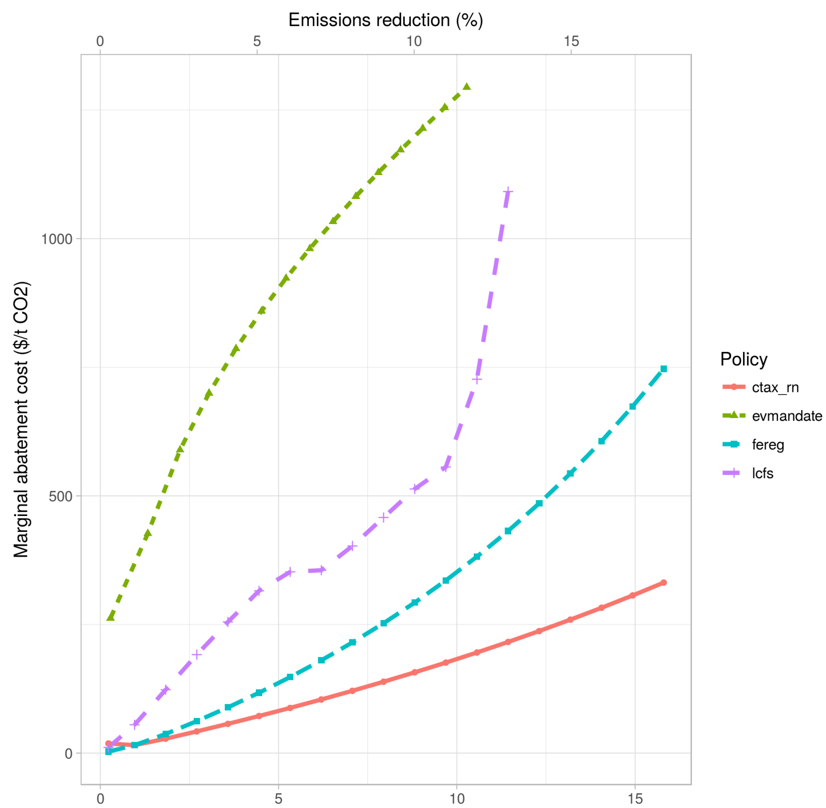
6.1 Network Effects and EV Pessimism

Figure 2 shows the marginal abatement costs corresponding to having neither network effects or EV pessimism (NN), having very strong network effects (USN), and significant cost errors (NNEE). The marginal abatement cost curves for the carbon tax and LCFS are not much changed in the network/error configurations. This is because the changes affect channels which are of relatively little direct importance to these policies.

The cost-effectiveness of the fuel economy regulations is improved more than that of the carbon tax and LCFS since the parameter changes affect the costliness of adding EVs, which is one response spurred by the fuel economy regulations. The relative cost-effectiveness of the carbon tax, LCFS and fuel-economy regulation instruments is affected by the parameter changes.

[7] The fuel economy regulations perform better than the EV mandate because the regulations also give incentives to switch among IC vehicles towards more fuel-efficient vehicles.

Figure 1: Cost Effectiveness: No Network Externalities or Cost Errors



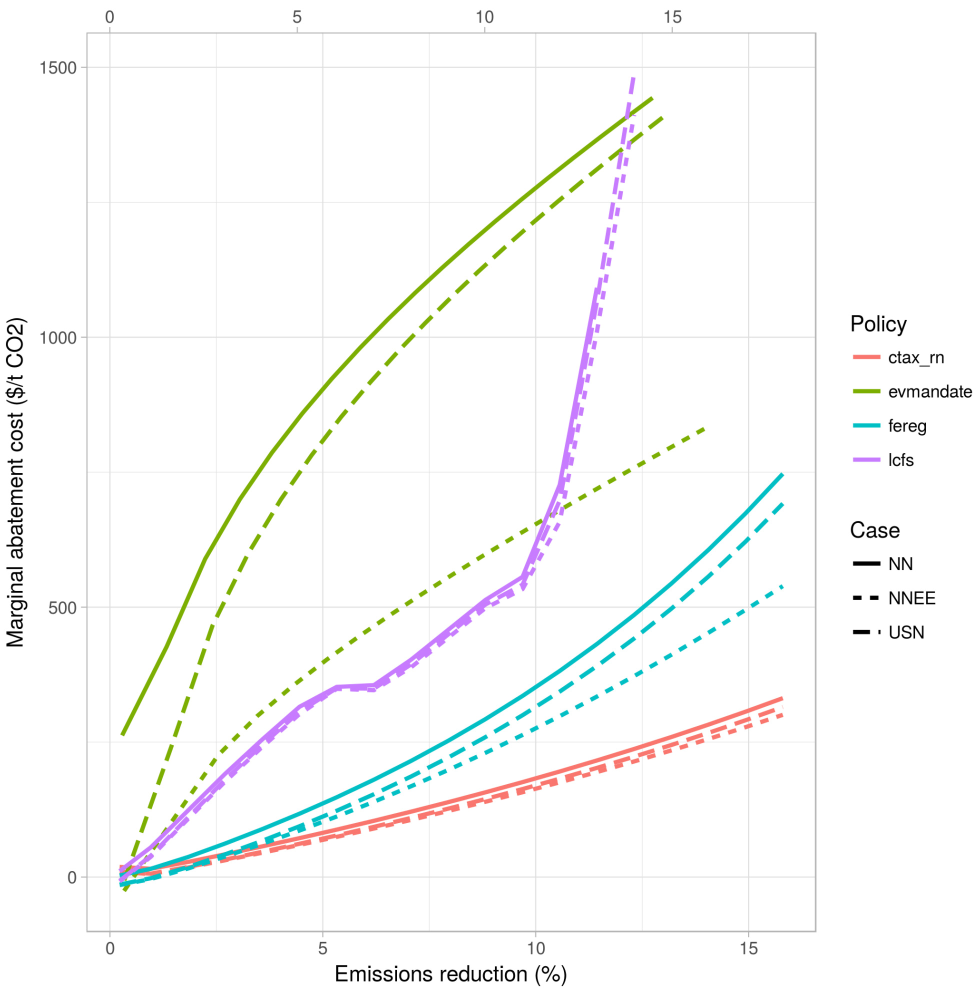
For very small emission reduction targets, and only in the case of very strong EV pessimism the EV mandate is the most cost-effective instrument. With that slight proviso, the carbon tax and fuel economy regulation remain the most cost-effective instruments.

The relative cost-effectiveness of the LCFS and EV mandate can be changed markedly by the addition of network and cost-error considerations. This is true both for very low levels of abatement, where in the NNEE case, the EV mandate dominates for emission reductions over 10%.

When EV pessimism is strong because the marginal abatement cost curve for the EV mandate starts below the X-axis, meaning that initial reductions in GHG emissions generate welfare gains even exclusive of their environmental benefits.

Because we have no evidence about the likely size of either the cost overestimates or network effects it is rather tenuous to infer which is more important. Having said that, even with what would seem to be fairly substantial network effects the impact of the 20% cost errors is significantly larger. Because the network effects are modeled in the same way as learning effects, the 10% network effect initially translates into a much *larger* cost reduction because the number of EVs in some of our experiments is more than doubling. To achieve the 10 Mt target via EV mandate alone for example, the network effect reduces the overall cost of ‘driving an EV’ by over 45%.

Figure 2: MAC Sensitivity



7 Policy Packages

Rivers and Wigle (2018b) looks at the least-cost package of EV mandate and LCFS *given* pre-existing commitments as far as carbon pricing and tightened fuel-economy regulation in Canada. These results include no network effects or EV pessimism. As shown in Figure 3 the EV mandate initially plays no role for more modest reduction targets, and then plays a rather modest role for targets up to a reduction of about 10 Mt. Thereafter the LCFS and EV Mandates are tightened at similar rates.

The policy packages shown in figures 3–5 are labelled with the (rounded) percentage change in emissions associated with each point. So for example, referring to Figure 3 the policy package labelled 14 (10% EV mandate and 9% LCFS) leads to emission reductions in road transport of about 14% corresponding to emission reductions in road transport of about 12 Mt. Emission reductions for the policy packages are calculated relative to a policy baseline including legislated

To show the relative impact of changng the strength of network effects and EV pessimism on the optimal policy package we first show the effects of different strengths of the network effects on

Figure 3: Policy Package: No Network Effects or EV Pessimism Errors

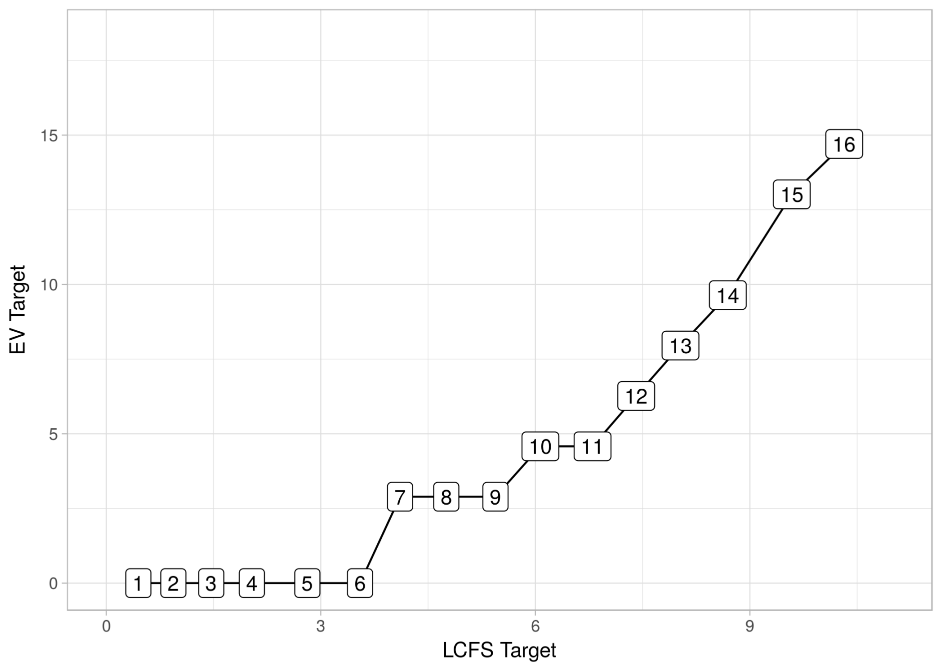


Figure 4a and then look at different strengths of EV pessimism in Figure 4b.

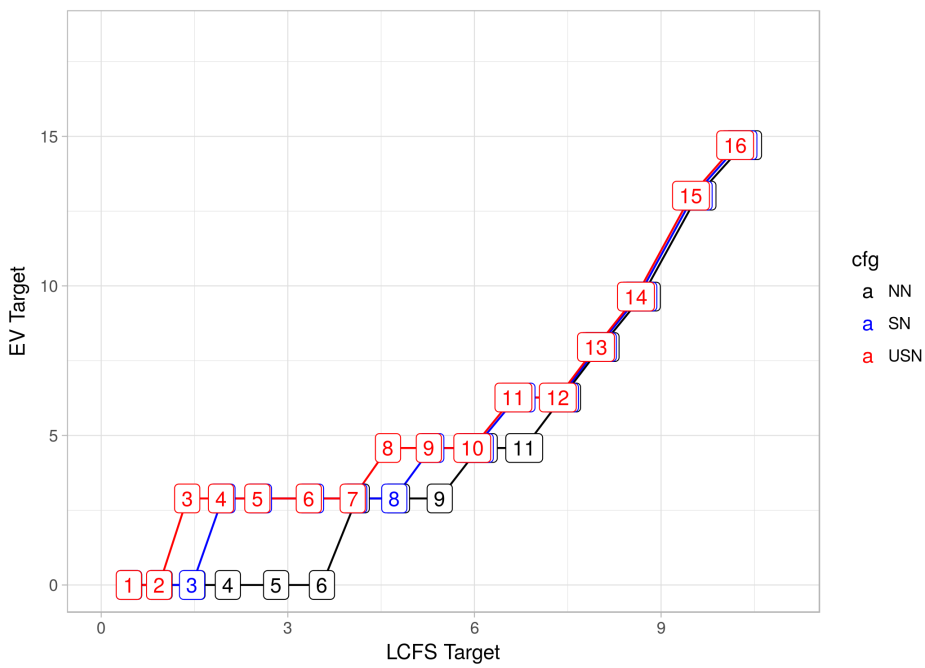
With no network effects, optimal policy packages for reducing road transport emissions by up to 6% involve no EV mandate. With a 10% network effect the EV mandate is forgone as far as 3% emissions reduction. With a very strong network effect (15%) the EV mandate is introduced after the emissions reduction rises above 2%. While the EV mandate is introduced earlier as the network effects grow, its influence on the policy package diminishes as the emission reduction target increases. This is in part due to the nature of the network effect, which is strongest for smaller increases in EV share.

The introduction of 10% EV pessimism leads to a binding EV mandate once the emission reduction target rises above 2%. With stronger EV pessimism, the EV mandate is introduced even earlier (when the reduction target exceeds 1%). In contrast to the network effect, EV pessimism shifts the entire policy package curve up. In contrast to the the case of network effects the EV mandate in the policy package to achieve a 16% reduction rises from under 15% with no EV Pessimism to just over 18% with 20% EV pessimism.

Finally Figure 5 shows how adding network effects and EV pessimism together changes the cost-minimizing package sometimes significantly. As noted before, adding strong network effects alone (case USN) motivates higher EV mandates as part of the policy package, but only when we combine this with strong EV pessimism is the EV mandate part of the optimal package right from the outset. In contrast to all other cases considered, the EV mandate is used **before** the LCFS in this case and continues to play a more important role at an earlier stage.

Figure 4: Policy Packages: Network Effects and EV Pessimism

(a) Network Effects



(b) EV Pessimism

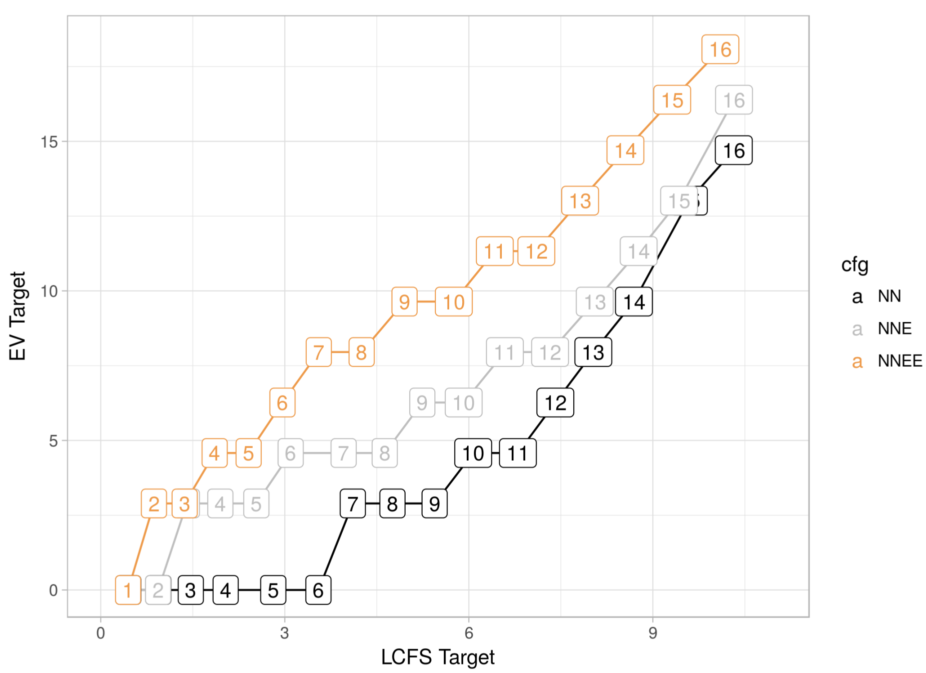
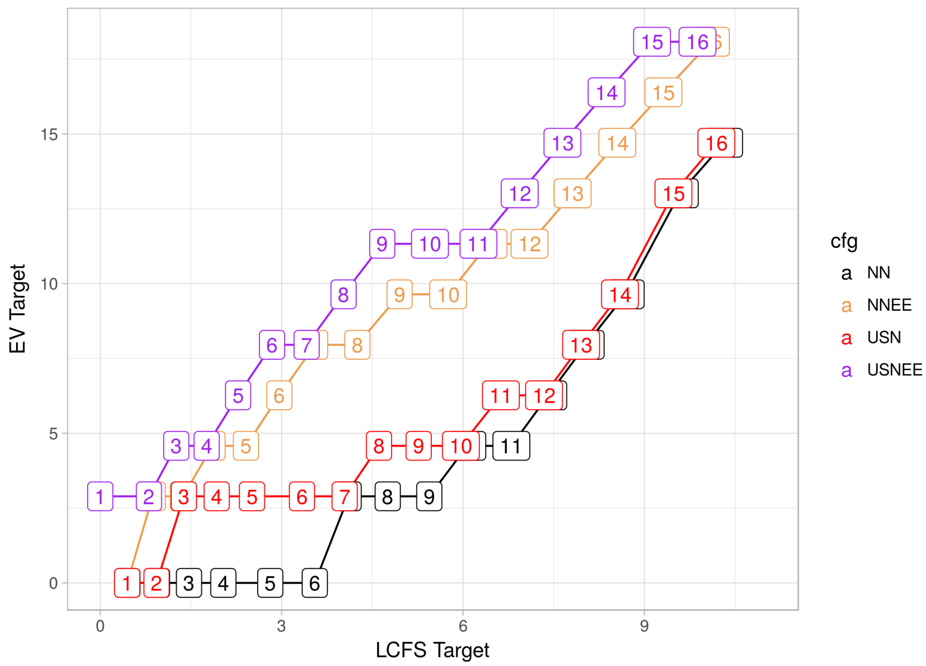


Figure 5: Policy Packages: Network Effects and EV Pessimism Errors



7.1 Cost-Effectiveness

Returning to the theme of cost-effectiveness, the MAC curves corresponding to the revenue neutral carbon tax and optimal policy package are compared for the four polar cases considered, that is:

NN No network effect or EV Pessimism[8]

NNEE No Network 20% EV Pessimism

USN CC but 15% network effect

USNEE CC but 15% network effect and 20% EV Pessimism

Note that the MAC curves in Figure 6 correspond to reductions on top of our estimated impacts of the announced policy baseline which includes carbon tax increases and fuel economy regulation. This is why the MAC of the revenue-neutral carbon tax for 10% on Figure 6 corresponds to a reduction of about 12.5% in Figure 1.

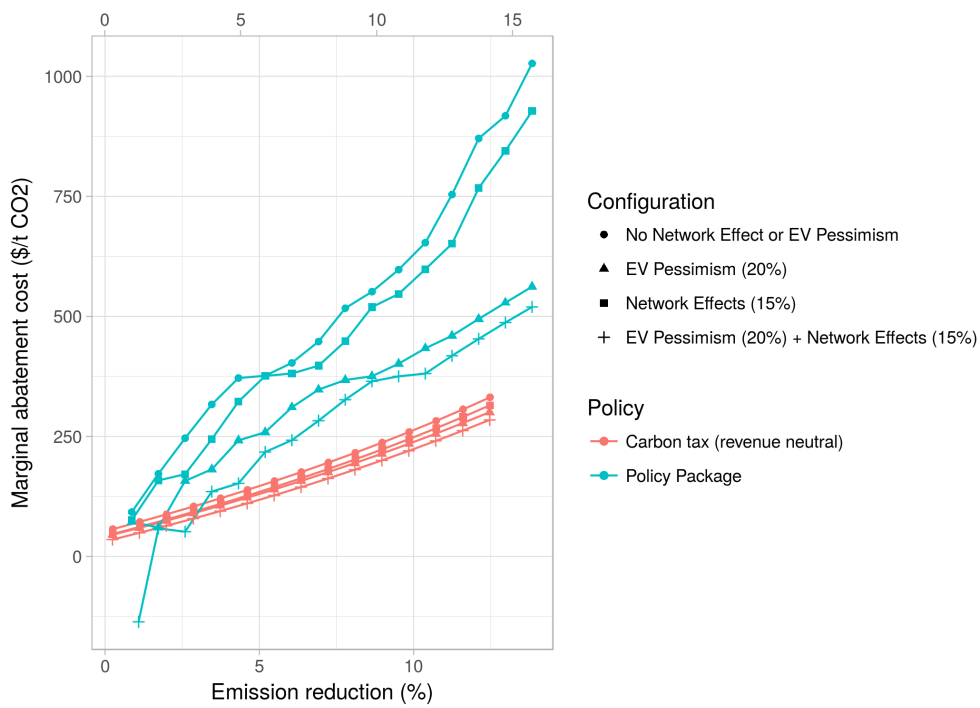
Stronger EV Pessimism and network effects affect the cost-effectiveness of the optimal policy package in different ways. Stronger network effects have less impact than the strong network effects. Only in the case of EV pessimism and network effects that are both strong, a policy package including an EV mandate is initially more cost-effective than a revenue neutral carbon tax.

EV pessimism might be expected to shift the MAC curve for the EV mandate down in a parallel way, since an added error correction equal to the pessimism would seem to be appropriate. Similarly, network effects might be expected to shift the MAC curve down with the biggest impact corresponding to lower EV targets. Neither of these expectations is strongly reflected in Figure 6. As the share of EVs rises, the corresponding percentage change of a given increase in EV share will fall leading to a smaller change in the network effect.

In the most favourable parameter configuration (USNEE), the associated policy package is roughly competitive with a carbon tax up until an emission reduction target of 5%. Thereafter, even in this instance the policy package becomes increasingly less cost-effective as the emission reduction increases. Having said this, the contrast between the policy package and the carbon tax is much less stark than if one ignores network effects and EV pessimism.

[8] This corresponds to the Central Case in Rivers and Wigle (2018a,b).

Figure 6: Marginal Abatement Cost: Policy Package and Carbon Tax



8 Summary

This somewhat speculative analysis yields a number of suggestive findings:

EV Pessimism Adding 20% EV pessimism reduces the social cost of reducing GHGs with an EV mandate. The impact of adding this feature is particularly strong for low levels of emissions reductions. As well, the role of the EV mandate is expanded correspondingly within our least-cost policy package.

network effects Adding rather strong network effects improves the cost-effectiveness of the EV mandate but modestly. As well, the role of the EV mandate is expanded very modestly, and only at lower levels of emission reduction.

policy package cost The cost effectiveness of the least cost policy package is significantly improved relative to the central case, but the package is only more cost-effective than a pure carbon tax for modest reductions in road transport emissions.

Our conclusions are necessarily speculative because of the lack of empirical evidence on which to base our formulations. Having said that, the findings of this paper suggest that even adding network effects and EV pessimism an EV mandate on its own is unlikely to be a cost-effective instrument to make significant GHG emission reductions. Alternatively, the case for an EV mandate to be part of a cost-effective policy package for more strict reduction targets would require even stronger EV pessimism and/or network effects.

Put another way, although these features don't override the qualitative argument that EV mandates are not cost-effective, they do offer a different perspective as far as the **extent** to which they might be cost in effective. With either significant EV pessimism and/or network effects, EV mandates are less than twice as costly as the carbon tax. This contrasts with earlier estimates where an EV mandate was higher than 3 times as costly as a carbon tax.

References

Adler, J. D., P. B. Mirchandani, G. Xue, and M. Xia (2016). The electric vehicle shortest-walk problem with battery exchanges. *Network and Spatial Economics 16*, 155–173.

Allcott, H. and N. Wozny (2014). Gasoline prices, fuel economy, and the energy paradox. *Review of Economics and Statistics 96*(5), 779–795.

Anderson, S., C. Fischer, and A. Egorenkov (2016). Overlapping strategies for reducing carbon emissions from the personal transportation sector. Discussion paper, Resources for the Future.

Ballard, C. (2000). How many hours are in a simulated day? the effects of time endowment on the results of tax-policy simulation models. *Unpublished paper, Michigan State University*.

Barla, P. (2018, March). Comment on "Costs and Benefits of Quebec's Drive Electric Program". *Canadian Public Policy*, 77–79.

Barla, P., B. Lamonde, L. F. Miranda-Moreno, and N. Boucher (2009). Traveled distance, stock and fuel efficiency of private vehicles in Canada: price elasticities and rebound effect. *Transportation 36*(4), 389–402.

Busse, M. R., C. R. Knittel, and F. Zettelmeyer (2013). Are consumers myopic? evidence from new and used car purchases. *The American Economic Review 103*(1), 220–256.

Cahuc, P., S. Carcillo, and A. Zylberberg (2014). *Labor Economics*. MIT press.

Cazzola, P., G. Morrison, H. Kaneko, c. C. Fran A. Ghandi, and L. Fulton (2013). Production costs of alternative transportation fuels: Influence of crude oil price and technology maturity. Featured insight, International Energy Agency.

Chandra, A., S. Gulati, and M. Kandlikar (2010). Green drivers or free riders? an analysis of tax rebates for hybrid vehicles. *Journal of Environmental Economics and Management 60*(2), 78–93.

Coglianese, J., L. W. Davis, L. Kilian, and J. H. Stock (2017). Anticipation, tax avoidance, and the price elasticity of gasoline demand. *Journal of Applied Econometrics 32*(1), 1–15.

Dragicevic, A. (2017, September). Spacetime discounted value of network connectivity. Conference paper, FAERE Annual Conference 2017. Paper available at `http://faere.fr/pub/Conf2017/FAERE2017_Dragicevic.pdf`.

Farahani, R., E. Miandoabchi, W. Szeto, and H. Rashidi (2013). A review of urban transportation network design problems. *European Journal of Operational Research 229*(2).

Fischer, C., W. Harrington, and I. W. H. Parry (2007). Should automobile fuel economy standards be tightened. *Energy Journal 28*(4), 1–29.

Fullerton, D. and S. E. West (2002). Can taxes on cars and on gasoline mimic an unavailable tax on emissions? *Journal of Environmental Economics and Management* (43), 135–157.

Gillingham, K. (2014). Identifying the elasticity of driving: evidence from a gasoline price shock in california. *Regional Science and Urban Economics 47*, 13–24.

Gillingham, K., F. Iskhakov, A. Munk-Nielsen, J. P. Rust, and B. Schjerning (2019, May). Equilibrium trade in automobile markets. Working Paper 25840, National Bureau of Economic Research. In `transport_ghg/references/GE-model-vehicle-85729-w25840.pdf`.

Gillingham, K. and A. Munk-Nielsen (2016). A tale of two tails: Commuting and the fuel price response in driving. Working paper, National Bureau of Economic Research.

Goulder, L. H., I. W. Parry, R. C. Williams Iii, and D. Burtraw (1999). The cost-effectiveness of alternative instruments for environmental protection in a second-best setting. *Journal of Public Economics 72*(3), 329–360.

Greene, D. L., P. D. Patterson, M. Singh, and J. Li (2005). Feebates, rebates and gas-guzzler taxes: a study of incentives for increased fuel economy. *Energy policy 33*(6), 757–775.

Hardman, S., A. Jenn, G. Tal, J. Axsen, G. Beard, N. Daina, E. Figenbaum, N. Jakobsson, P. Jochem, N. Kinnear, P. Pltz, J. Pontes, N. Refa, F. Sprei, T. Turrentine, and B. Witkamp (2018). A review of consumer preferences of and interactions with electric vehicle charging infrastructure. *Transportation Research Part D: Transport and Environment 62*, 508 – 523.

He, F., Y. Yin, and S. Lawphongpanich (2014). Network equilibrium models with battery electric vehicles. *Transportation Research Part B 67*, 306–319.

Holland, S. P., J. E. Hughes, and C. R. Knittel (2009, February). Greenhouse gas reductions under low carbon fuel standards? *American Economic Journal: Economic Policy 1*(1), 106–46.

Huang, Y., S. Li, and Z. S. Qian (2015). Optimal deployment of alternative fueling stations on transportation networks considering deviation paths. *Networks and Spatial Economics 15*(1).

Irvine, I. (2017, March). Electric vehicle subsidies in the era of attribute-based regulations. *Canadian Public Policy 43*(1), 50–60.

Litman, T. (2004). Transit price elasticities and cross-elasticities. *Journal of Public Transportation 7*(2), 3.

Loveys, M. (2017, August). Economists are wrong on electric vehicle subsidies. *Policy Options*.

Mercier, X., P. Lanoie, and J. Leroux (2015, December). Costs and benefits of Québec's drive electric program. *Canadian Public Policy 41*, 281–296.

Meunier, G. and J.-P. Ponssard (2018, April). Optimal policy and network effects for the deployment of zero emission vehicles. Working Paper 7026, CESifo. Category 10: Energy and Climate Economics, available at `transport-ghg/references/network/policy-network-EV.pdf`.

Ministry of Mines and Energy (2014). Renewable and low carbon fuel requirements regulation: Summary for 2012. Information Bulletin RLCF-007-2012, British Columbia. Revised July, 2014.

Moorhouse, J. (2017, July). Canadian Clean Fuel Standard: Modelling results and conclusions. Slide presentation, Clean Energy Canada. Supplied by the author.

Parry, I. W., R. C. Williams III, and L. H. Goulder (1999). When can carbon abatement policies increase welfare? the fundamental role of distorted factor markets. *Journal of Environmental Economics and Management 37*(1), 52–84.

Paulley, N., R. Balcombe, R. Mackett, H. Titheridge, J. Preston, M. Wardman, J. Shires, and P. White (2006). The demand for public transport: The effects of fares, quality of service, income and car ownership. *Transport Policy 13*(4), 295–306.

Rivers, N. and B. Plumptre (2016). The effectiveness of public transit subsidies on ridership and the environment: Evidence from Canada. Working paper, University of Ottawa, Institute of the Environment.

Rivers, N. and B. Schaufele (2017a). Gasoline price and new vehicle fuel efficiency: Evidence from Canada. *Energy Economics 68*(Supplement C), 454 – 465.

Rivers, N. and B. Schaufele (2017b). New vehicle feebates. *Canadian Journal of Economics/Revue canadienne d'économique 50*(1), 201–232.

Rivers, N. and R. M. Wigle (2018a, January). An evaluation of policy options for reducing greenhouse gas emissions in the transport sector: The cost-effectiveness of regulations versus emissions pricing. Working Paper 2018-1, LCERPA. `http://www.lcerpa.org/public/papers/LCERPA_2018_1.pdf`.

Rivers, N. and R. M. Wigle (2018b, February). Reducing Greenhouse Gas Emissions in Transport: All in One Basket? Briefing Paper Volume 11:5, School of Public Policy. `https://www.policyschool.ca/wp-content/uploads/2018/01/GHG-Emissions-Rivers-Wigle.pdf`.

Sallee, J. M., S. E. West, and W. Fan (2016). Do consumers recognize the value of fuel economy? evidence from used car prices and gasoline price fluctuations. *Journal of Public Economics 135*, 61–73.

Vass, T. and M. Jaccard (2017, June). Driving decarbonization: Pathways and policies for Canadian transport. Working paper, Energy and Materials Research Group (EMRG) School of Resource and Environmental Management, Simon Fraser University.

Wood, J. (2015). Is it time to raise the gas tax? optimal gasoline taxes for Ontario and Toronto. *Canadian Public Policy 41*(3), 179–190.

Xiang, Y., J. Liu, R. Li, F. Li, C. Gu, and S. Tang (2016). Economic planning of electric vehicle charging stations considering traffic constraints and load profile templates. *Applied Energy 178*, 47–659.

Zhang, W. and Y. Dou (2019, February). Government subsidy design for electric vehicle and charging markets. Technical report. `transport_ghg/references/charge-vs-vehicle-subsidies.pdf`.

Zheng, H., X. He, Y. Li, and S. Peeta (2017). Traffic equilibrium and charging facility locations for electric vehicles. *Network and Spatial Economics 17*, 435–457.

A 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),[9] 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, 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

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

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.[10] 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.

A.1 Consumers

The model is based on the transportation decisions of a representative consumer. The consumer has an endowment of labour, which is denoted $\bar{L}$.[11] 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,

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

[11] 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 $\bar{L}$.

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.

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

A.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 A.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).

A.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.[12]

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

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.

A.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.

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

A.5 Rest of economy

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

A.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:

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

A.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.

A.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.

A.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.[13] Determination of the substitution other parameters is discussed below.

A.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 7.

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:

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

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

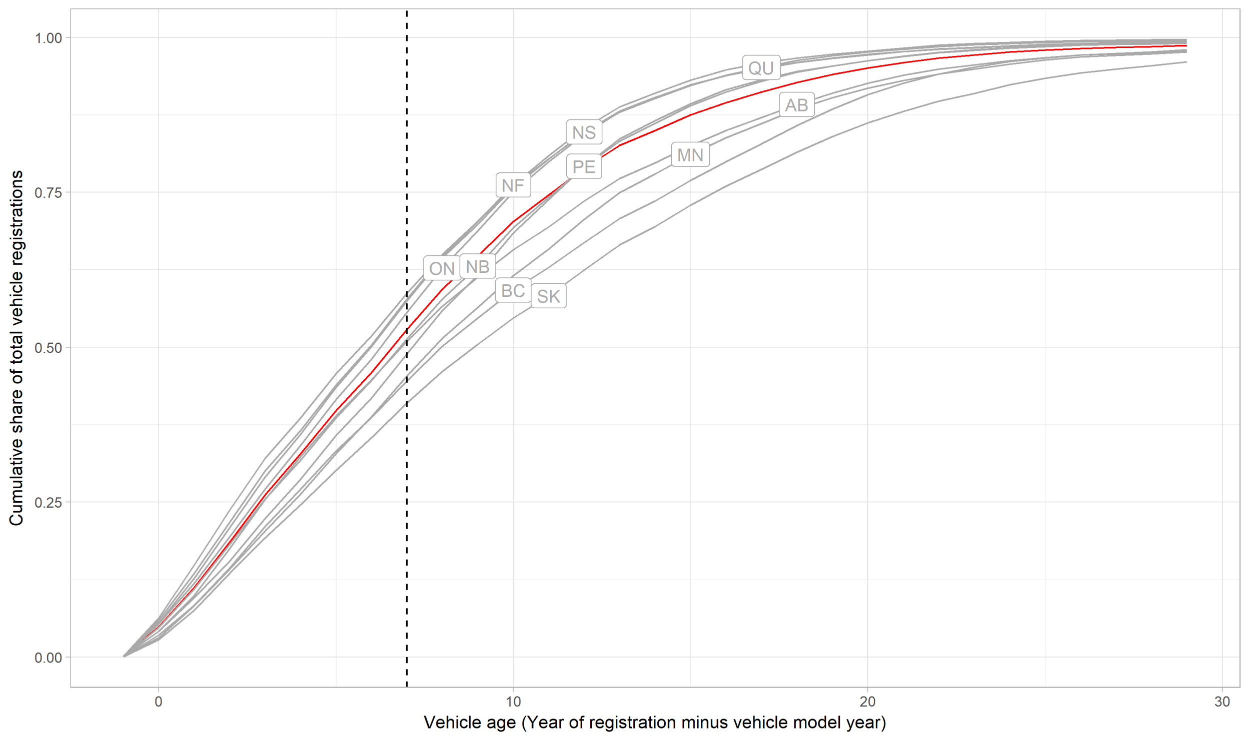


Figure 7: Age profile of existing vehicle stock. Author's compilation based on confidential vehicle registration data obtained from RL Polk and described in Rivers and Schaufele (2017b). Data corresponds to the year 2010.

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.[14] 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 economy. 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.

A.9 Calibration

We use a search approach to determine the values of σ_C and σ_T and $\bar{\sigma}_D$. 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 $\bar{\sigma}_D$ 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 $\bar{\sigma}_D$. We confirm that the resulting overall elasticity of demand for fuel reflects our target value.

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

A.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

B Additional Figures

Figure 8: Policy Packages: All Cases Considered