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Abstract: Like many jurisdictions, Canada has set a target of 2035 to eliminate sales of internal combustion engine vehicles (ICEVs) in favour of electric vehicles (EVs), for the purpose of reducing greenhouse gases. Past literature has focused on the engineering and economic aspects of integrating EVs into the passenger transportation system. Herein I examine the implications for the ICEV market of a phased-in EV mandate. I show using partial equilibrium analysis that, during the interval when both types of cars are available, auto companies will overproduce EVs and earn scarcity rents on ICEVs that partially offset the revenue loss from the mandate. I then present a numerical general equilibrium model of the Canadian economy to assess the macroeconomic consequences of banning ICEVs. The results depend critically on the pace at which EVs achieve cost parity with ICEVs on a quality-adjusted basis. An EV mandate will have temporary but manageable economic consequences if technology improves so rapidly that the mandate is effectively unnecessary. But if the mandate outpaces achievement of cost parity the economic consequences will be quite severe and make it unlikely the policy could be maintained. For example it would likely cause the auto manufacturing sector to shut down. The analysis also provides insight into why automakers have been so willing up to now to develop EV product lines even though they have long lost money on them and expect to continue doing so.

Keywords: Electric vehicles, climate policy, computable general equilibrium model.

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1 Introduction

Many jurisdictions, including Canada, have mandated that their auto sectors must switch over to electric vehicle (EV) sales such that new internal combustion engine vehicles (ICEV) will be all but outlawed by 2035 (Canada 2022). Analyses of the implications of expanding the EV industry have focused heavily on technical questions such as the likely trajectory of the costs of manufacturing batteries (Nykvist et al. 2019, Hsieh et al. 2019), implications for the electricity grid of the increased load (Schwab et al. 2022) and whether life-cycle carbon dioxide emissions rise or fall from switching to EVs (Neuegebauer et al 2022). Economic questions analyzed previously include the marginal costs of EV mandates relative to other policies (Rivers and Wigle 2018), life-cycle ownership costs (Raustad 2017) and consumer preferences regarding EVs. There is evidence that at present they mainly serve as secondary cars for affluent households (Burlig et al. 2021) and that sales are highly dependent on government subsidies (Paton 2019), which suggests they may have a limited voluntary market ceiling. Also since they tend to displace small, relatively fuel-efficient vehicles (Xing et al. 2021) the short-term potential for EV sales to yield greenhouse gas (GHG) emission reductions are small (Muehlegger and Rapson 2021).

This paper explores the question of how a phased-in EV mandate might affect the overall auto sector including the market for ICEVs, and the overall viability of the auto sector during the phase-in period. An EV mandate is a non-trivial policy. It amounts to a prohibition on one of the most popular and ubiquitous consumer products ever, the manufacture of which is a major part of the modern industrial economy. During the phase-in period both types of vehicles are available so people have the option to buy either an ICEV or an EV. In order to meet the binding sales mandate auto companies could raise the selling price of ICEVs thereby earning rents on each unit, but at the same time the overall vehicle market will shrink due to the rising purchase prices. I describe the effect of the mandate phase-in using a simple partial equilibrium model, then simulate its impact in a numerical general equilibrium model of the Canadian economy. The EV mandate allows the automotive sector to earn substantial economic rents on ICEV sales but these are more than offset by the overall drop in market revenue. The model suggests that, despite the ICEV rents, the EV mandate will push the Canadian automobile industry into a large loss position (and the overall economy into recession). Auto sector losses will last through the 2030s depending on how quickly EV production costs drop. The prospect of returning to a profitable state depends on optimistic assumptions about the pace at which the manufacturing cost of EVs dropping to parity with ICEVs for models that buyers consider to be perfect substitutes. At present there is not a sufficiently reliable empirical basis for determining if this is a likely outcome.

The next section discusses the EV mandate phase-in using a partial equilibrium model. Section 3 explains the numerical general equilibrium model of the Canadian economy, Section 4 discusses the simulation results and Section 5 presents Conclusions.

2 PHASING IN AN EV MANDATE

2.1 SIMULTANEOUS EV AND ICEV MARKETS

Auto companies offer both types of vehicles for sale. Suppose the mandate is that EV sales must be the fraction α of total sales in a given year. If q_1 denotes EV sales and q_2 denotes ICEV sales then $q_1/(q_1+q_2)=\alpha$ which implies $q_2=\theta q_1$ where $\theta=\frac{1-\alpha}{\alpha}$. Note that $\alpha \to 1 \Rightarrow \theta = 0$. Firms are assumed to be price-takers in the EV market. At current prices and even with substantial subsidies to buyers, EVs constitute a relatively small market segment in many countries and production costs are much higher than for comparably sized ICEVs. For a given level of EV sales θq_1 defines the maximum number of ICEVs that can be sold. If the profit functions for each market segment are, respectively, $\pi_1(q_1)$ and $\pi_2(q_2)$ then the combined profit function for the auto sector is $\pi(q_1, q_2) = \pi_1(q_1) + \pi_2(q_2)$. In the absence of a policy mandate the car companies would choose q_1 and q_2 separately yielding $\pi_1' = \pi_2' = 0$. The EV mandate means the joint profit function becomes $\pi(q_1, \theta) = \pi_1(q_1) + \pi_2(\theta q_1)$ which has a first-order condition $\pi_1' + \theta\pi_2' = 0$. If the sales constraint for ICEVs binds it must be the case that $\pi_2' > 0$, therefore $\pi_1' = -\theta\pi_2' < 0$. In other words during the EV mandate phase-in period, as long as $\alpha < 1$ the automakers will be on the downward-sloping part of the EV profit function, producing an above-optimum number of EVs in order to increase the number of ICEVs they can sell. Also note that as long as $\theta q_1 < q_2$ it must be the case that $\pi_1(q_1) + \pi_2(\theta q_1) < \pi(q_1, q_2)$, in other words despite the possible rents in the ICEV sector, total auto sector profits will be below the unrestricted level, something that will be confirmed in the numerical simulations.

Denote the unrestricted optimum sales levels as q_i^* and the jointly-optimized EV and ICEV production levels under the mandate as $\tilde{q}_i$, $i = 1,2$. Figure 1 shows the effect in the twin car markets on the assumption that marginal production costs for both vehicle types are constant but higher for EVs than for ICEVs. The Figure also assumes that current demand is lower for EVs and has a higher (negative) demand elasticity. When ICEV sales (right panel) are capped at $\theta\tilde{q}_1$ the firms in that market segment restrict production and earn the rents shown as the striped rectangle. They also overproduce EVs and sell the marginal units at a loss as indicated by the shaded area in the left panel. As the mandate tightens, for a given level of $\tilde{q}_1$ the rent rectangle in the ICEV market will at first grow then shrink to zero.

Depending on the magnitude of the gains and losses in the two markets the phase-in of an EV mandate can thus, at first, yield a potential net benefit to the ICEV sector, although not the auto sector as a whole. It allows manufacturers to act as an effective oligopoly, constraining supply and generating rents. However as the mandated fraction of EV sales goes to 1 and $\theta \rightarrow 0$, the ICEV market and its temporary rents disappears. Also, automobile production has large fixed costs so even with the rents shown in Figure 1, the reduced sales quantity means that average costs may exceed average revenues overall and the sector may operate at a loss. Finally, note that although Figure 1 assigns the rents to the respective market segments, in practice the EV side would likely capture some of the rents from the ICEV side if implementation involves tradable compliance permits. This would be the case if, for example, an EV manufacturer is awarded tradable credits which an ICEV manufacturer could purchase instead of having to produce EVs themselves.

The prospect that automakers may sell EVs at a loss is already of concern to the industry. In a submission to the government of Quebec in 2016, which was then considering imposing an EV sales mandate, the Canadian Vehicle Manufacturers Association (CVMA) warned that its members are already incurring substantial losses on each EV unit produced:

> [Estimated] vehicle manufacturers losses are in the range of $12,000 to $20,000 per [plug-in hybrid EV] or [battery EV]. The sale of electric cars currently and for the foreseeable future will require significant automaker subsidies (in addition to government consumer

> incentives already in place). As with any business or industry, there is only so much subsidization that can occur before the underlying economics of designing, manufacturing and selling automobiles in the market is compromised and unsustainable.
>
> Source CVMA (2016) p. 6

See also Colias (2023), which reports that Ford expects to lose US$3b on EVs in 2023. These losses, it should be noted, are being incurred before the imposition of a binding EV sales mandate. In other words, the sector currently can choose to operate where $\pi_1' = 0$ but average costs still exceed average revenues. While a limited EV mandate could benefit automakers by allowing them to earn rents on ICEVs, at the same time it will shrink the total sales volume. As $\theta \to 0$ and the sector converges on an outcome where $\pi_1'(q_1^*) = 0$ and $q_2 = 0$, unless average costs of production fall below average revenues the auto sector will be facing permanent losses.

In the next section we examine the consequences for the Canadian economy of phasing in an EV mandate using a model that takes account of the pricing effect described above and embeds it into a large-scale computable general equilibrium model. We find in the short run that positive rents are generated on the ICEV side but they do not compensate for the overall loss of revenue as the total automobile market shrinks due to the required increase in the price of cars. The model predicts that the losses will run a long time depending on how quickly EV production costs fall.

3 SIMULATION MODEL OF EV TRANSITION

3.1 MAIN DESCRIPTION OF MODEL

The model to be employed herein is version 6.0 of one originally presented in Lee and McKitrick (2020) and is called the LFXCM.[1] It resolves annual economic activity in each of 10 Canadian provinces and the northern territories jointly, thus covering 11 jurisdictions. The model is written in the R language (R Core Team 2022) and the code is available at McKitrick (2023). The model is solved annually over the 2019 to 2050 interval and relies on myopic, recursive dynamics rather than rational expectations-driven processes, which, as will be discussed below, represents a tradeoff between achieving enhanced static detail and more theoretically-consistent dynamics. An exogenous growth rate is applied to the population using projections from the Conference Board of Canada (2021). Within each jurisdiction there is a single aggregate household which supplies labour and owns capital. Production occurs in 26 sectors which are listed in the Appendix. Trade occurs inter-provincially and internationally. The government in each jurisdiction is represented on a consolidated basis, combining provincial and federal operations. The government collects taxes, services its debt, purchases labour, goods and services, and supplies transfers to households.

The current-period household utility function combines demand for leisure H and consumption C with associated prices w (wage rate) and p (aggregate goods and services price index), time endowment T (leisure H plus labour L) and exogenous income Y. The utility function is $U = \frac{\gamma}{\alpha} H^{\alpha} + C$ where γ is a scaling parameter. This is optimized against the budget constraint $wH + pC = Tw + Y$ using a Lagrangian function $\ell = U - \lambda(wH + pC - Tw - Y)$. The first-order conditions yield:

[1] This stands for LFX Associates Canadian Model.

$$\lambda = \frac{1}{p} \qquad [1]$$

and

$$H = \left(\frac{1}{\gamma}\right)^{\frac{1}{\alpha-1}} \left(\frac{w}{p}\right)^{\frac{1}{\alpha-1}}. \qquad [2]$$

These can be solved to obtain an endogenous labour supply function

$$L = T - \theta \left(\frac{w}{p}\right)^{\sigma}$$

where $\theta = \gamma^{\frac{1}{1-\alpha}}$ is a scaling parameter and $\sigma = \frac{1}{\alpha-1}$ is a parameter that determines the elasticity of leisure demand with respect to the real wage rate.

Consumption C is disaggregated through a series of nesting operations listed in the Appendix. At each nesting level the consumer derives optimal nominal budget shares using a Constant Elasticity of Substitution (CES) aggregator and the implementation in the model follows the derivation in Shoven and Whalley (1992). Elasticity parameter selection is described in the Appendix. Producers disaggregate intermediate input demands using a CES aggregator that yields endogenous input-output coefficients following the derivation in Berck and Sydsaeter (1993). Thus, for a given price vector, the model computes nominal share functions for households and input-output coefficients for firms.

Within a province, given prices, tax rates, government spending and trade volumes the model yields the intermediate input-output (IO) coefficient matrix A, and final demands for consumption C, government purchases G, investment or Gross Fixed Capital Formation I, exports X and imports M. Denote $C + I + G + X - M = F$. If real output is denoted Q the Leontief market clearing condition is $AQ + F = Q$. The model solves for Q using the matrix equation $Q = (I - A)^{-1}F$. This clears all goods and service markets at the existing prices, which is equivalent to assuming constant returns to scale in each sector. Then input-output coefficients for labour and capital are used to determine factor demands by sector and province. The capital supply is determined using a capital dynamics equation described below. Capital utilization within a sector and within a province is the ratio of the current capital demand and the start-of-period capital supply. Exogenous restrictions are imposed on the Education and Health care sector in some provinces to limit its expansion since it is primarily governed by government policy and cannot respond freely to market conditions.

Since the Leontief equation is solved for each province, and some provinces are net importers of some goods (for example, Ontario imports crude oil for refining), the equilibrium output level can be negative. If the labour IO coefficient were applied it would yield a negative demand for labour. This is an implication of the “cross-hauling” phenomenon in which provinces can both import and export the same commodity, such as food for instance. The relevant labour demand level is therefore based on final demand before subtracting imports, which equals $(C + I + G + X)$. This yields, for example, an employment level of zero for oil sands production in Ontario, which is the appropriate estimate. The model uses the pre-import final demand amount as the basis for estimating labour demand in each sector and province.

The model adjusts the national wage rate to clear the national labour market, the capital price to equate the demand for capital with the current capital stock, the international exchange rate to balance the currency inflows and outflows and the real interest rate to balance savings and investment. Labour markets within a jurisdiction do not necessarily clear: there can be surpluses or shortage of labour within a province but they add up to zero nationally. The program verifies that unit profits are zero within each sector and Walras' Law holds nationally at every iteration.

3.2 INVESTMENT, CAPITAL FLOWS AND TRADE

The model uses the Statistics Canada (2022a) provincial input-output tables to determine the nominal operating surplus $\pi_{i,j}$ in each sector i in each jurisdiction j. The user cost of capital u is computed as the price of capital less its discounted resale value net of depreciation:

$$u = p_k - p_k \frac{1-\delta}{1+r_t} = p_k \frac{(r_t + \delta)}{1+r_t}$$

where p_k is the price of capital, r_t is the real interest rate and δ is the depreciation rate. Note the user cost of capital is increasing in the real interest rate and the price of capital. A sector's operating surplus should tend in equilibrium to cover its user cost of capital, thus $\pi_{i,j} = uK_{i,j}$. We compute the average gross operating surplus $\bar{\pi}_{i,j}$ for each sector in each province over 2014-2018 and generate the estimated 2019 starting capital stock using $\bar{\pi}_{i,j}/u$. Capital demand is determined each period as part of the computation of equilibrium and the price of capital adjusts to clear the national capital market.

The capital stock then evolves using the standard discrete function $K_{i,j}(t+1) = (1-\delta) \times K_{i,j}(t) + I_{i,j}(t)$ where t is time, $I_{i,j}$ is gross fixed capital formation and δ is the depreciation rate which is assumed to be 3%. There is a large and longstanding debate in economics (which won't be reviewed here) over how to model fixed capital investment demand in an empirically credible, computationally feasible and theoretically-sound way. The approach used herein is by no means intended as a solution to this longstanding quest, only as a potentially useful and defensible method. We use Tobin's q theory, in which investment demand is assumed to be driven by the ratio of the market value of physical capital to its replacement cost. The intuition is sound, in the sense that current market value is an indication of the expected payoff of owning that type of capital. If it exceeds the cost of replacing the asset the market will order more such units built, whereas if the ratio is less than unity the market will not replace the current units and allow them to depreciate. As explained in Andrei et al. (2018) Tobin's q models performed quite poorly for a long time but after the mid-1990s have found strong support in the data, including R^2 values of about 70% for simple regression equations of the form $\frac{I(t+1)}{K(t)} = \beta_0 + \beta_1 q(t) + \varepsilon(t)$.

To make this result operational in the present model, note that the demand for capital within a sector is $a_{i,j}^K Q_{i,j}$ where $a_{i,j}^K$ is the IO coefficient for capital, based on optimization with respect to current prices, and $Q_{i,j}(t)$ is the current output level consistent with the market-clearing equilibrium. Thus $p_i a_{i,j}^K$ is the value marginal product of capital in the sector at current prices. The price at which the current capital stock trades is p_K, but the replacement cost is based on the cost of new fixed capital formation. The Canadian input-output tables provide estimates of the allocations of spending on gross fixed capital formation across sectors: for instance about 50 percent is spent on construction and about 6 percent on motor vehicles. These shares are only identified at the provincial level, not at the individual sectoral level. However this suffices to construct a price index for each province of the replacement cost of capital, which we denote p_j^{RK}. Hence for each sector in each province Tobin's $q_{i,j} = p_i a_{i,j}^K / p_j^{RK}$. Fixed capital formation is assumed to be undertaken by the aggregate household in each jurisdiction which accesses financial resources to fund investment. Our simplified q model follows the estimates in Andrei et al. (2018, see Table 4) and takes the form $I_{i,j}(t) = (0.01 + 0.011 q_{i,j}) K_{i,j}(t)$. This expression is augmented with a multiplicative term that adjusts for the growth of the labour supply each year and is used to compute fixed capital formation in each sector and the next period's capital stock.

One point to note about this treatment of investment is that variations in capital formation are driven by changes in the relative prices of goods and services, but since constant returns are imposed, price changes tend to be dampened and policy shocks tend more to affect market quantities. Hence the response of fixed capital formation to policy-induced price changes will likely be understated in this model compared to the real economy. Usage of the pre-existing capital stock by sector responds freely to price changes through the $a_{i,j}^K$ coefficients, but the representation of policy-induced changes to the evolution of the overall capital stock over time is likely inadequate.

Imports and exports are handled in an ad hoc way. Inter-provincial imports and exports are based on the 2018 levels shown in the IO tables, adjusted over time to grow with the size of the labour force. International trade is estimated using the 2018 trade volumes adjusted to grow with the size of the labour force and further adjusted with two parameters. The first adjusts export and import volumes based on exchange rate changes using elasticities reported in Bussière et al. (2017) specifically the estimates after applying product-year fixed effects. The second adds a further adjustment to exports of oil, gasoline and natural gas in response to changes in the world prices of these specific commodities. For most years these prices do not change, but during the COVID-19 recession and its aftermath there were some assumed price adjustments. Since they are applied under both the base case and policy experiment run they have no effect on the impacts of the EV mandate experiments. Finally import demands are assumed to change if domestic prices change relative to their foreign counterparts, using the same elasticity as is applied to import responses to exchange rate changes.

3.3 TAXES AND REGULATIONS

The model uses information in the IO tables to compute both input and output indirect tax rates for each commodity in each province. Average income tax rates were computed using government income tax revenues by jurisdiction from Statistics Canada (2022b) and total labour compensation from the IO tables; likewise average capital income tax rates for each jurisdiction were computed the same way.

3.4 HOUSEHOLD SAVINGS, FOREIGN BORROWING AND THE COVID RECESSION

The real interest rate each period adjusts to equilibrate demand and supply of investment funds. Domestic net savings consist of household savings plus the government budget surplus. Household savings is assumed to be a fraction of total income determined empirically by a regression of the household savings rate on the estimated real interest rate. The data sample runs from 1991 to 2019 and the fit of the regression is highly significant. The savings rate each period (in % points) is given by $HSR_t = 1.503 + 1.075 \times r_t$ where r_t is the real interest rate (nominal bank rate deflated by the consumer price index). A fully dynamic model of the economy would begin with an intertemporal utility maximization model which would yield a savings function, then the model would solve for rational expectations-consistent consumption and investment paths for the 11 representative consumers. Because of the number of sectors in each province this approach would be computationally very demanding without necessarily yielding greater empirical fidelity. The empirical parameterization used herein is a compromise for feasibility. The household savings rate is additionally adjusted in 2020, 2021 and 2022 to match observed rates induced by the Covid pandemic lockdowns. These give rise to the contraction of domestic real consumption observed at the time.

Domestic demand for investment is determined by the national sum of nominal Gross Fixed Capital Formation. The difference between demand and supply of domestic investment funds determines the need for foreign borrowing. The supply of foreign funds available for domestic investment each period is determined using an empirical parameterization of the form $f.funds_t = f_0 + f_1 \times r_t \times \chi_t^{-1}$, where f_0 and f_1 are parameters estimated on recent investment flows data, r_t is the domestic real interest rate and χ_t is the ratio of the current and previous exchange rate (noting that an increase represents a depreciation).

3.5 AUTOMOBILE SECTOR AND THE EV MANDATE

Data for the automobile parts and assembly sector is taken from the provincial IO use tables. The Use tables have 543 rows, comprising individual inputs, taxes and payments to factors, and 554 columns, corresponding to intermediate industries and final demand sectors. The automotive manufacturing industry is defined herein as the sum of columns 104 to 114, which include car and truck manufacturers and all vehicle parts manufacturers. The IO tables do not distinguish between ICEV and EV manufacturers. The products are contained in rows 245 to 259 which includes passenger cars, light, medium and heavy-duty trucks, buses, trailers, motor homes, vehicle bodies and all vehicle parts. Again, EVs or EV components are not separately identified.

The policy mandate is for the auto sector to ensure the fraction α of auto sales is comprised of EVs. There is very little guidance in the literature on key parameter values, however Hosamaldin and Olofsson (2021) report a statistically significant elasticity value of 0.9 between the price of ICEVs and the market share of EVs. Suppose the EV fraction in the absence of a mandate is α_0. If the mandated value in period t is denoted α_t then the percent change in the ICEV price required to meet the mandated sales fraction is $(\alpha_t - \alpha_0)/0.9$.

We can expect, additionally, changes in EV production costs over the coming 30 years. It is very important to note that we are defining the cost parity to mean production on a quality-equivalent basis across the entire category of vehicles subject to the EV mandate. "Quality-equivalence" means achieving performance, convenience and reliability levels such that even dedicated ICEV users would be indifferent between EV and ICEV options. This includes not only size and acceleration characteristics but charging time, reliability in cold weather, towing capability, access to rapid charging options on all expected travel routes, etc. While the cost of manufacturing entry-level compact EVs has been steadily falling, some of the features that make for quality-equivalence especially for SUV and pickup truck models are either not falling or are falling much more slowly, especially those related to battery charge times and availability of charging infrastructure. As a result of learning-by-doing the cost of manufacturing EV batteries and the supporting infrastructure can be expected to drop (Nykvist et al. 2019), although current projections have been criticized as overly optimistic (Hsieh et al 2019). But due to the limited sources of some key mineral inputs, as worldwide production increases the marginal costs of production could go up rather than down. For instance the specific type of magnets critical to EV motor design (sintered neodymium iron-boron (NdFeB) magnets) are dependent on a supply chain that is almost entirely located in China, especially at the separation, refining and manufacturing stages (US Department of Energy 2022), raising the prospect that the government of China will exploit its market power.

In the absence of clear empirical guidance it will herein be assumed that of the two contrasting forces learning-by-doing has the stronger effect, but that owing to the ongoing challenges of achieving quality-equivalence for larger vehicles the net drop in production costs is linear rather than exponential. The ICEV cost premium is reduced the factor $(1 - \nu N)$ where N is the number of years after 2019 and ν is a parameter chosen so that quality-equivalent cost parity is achieved by an arbitrary date, though it is assumed that EV production costs do not go below those of ICEV's.[2] Combining these we get a function which yields the factor by which ICEV prices are inflated over the baseline level in each year in each province:

$$ICEV.premium(t) = \max\left(1 + \left(\frac{\alpha_t - \alpha_0}{0.9}\right)(1 - \nu N), 1\right) \qquad [3]$$

where t is the current year.

[2] If it were reasonable to suppose that, on a quality- and characteristic-equivalent basis, the cost of manufacturing EVs will fall below that of ICEVs on a foreseeable timetable, the EV mandate would not be needed. The premise of this policy experiment is that the EV mandate is needed through 2050.

Table 1 shows average values of the premium on ICEV vehicles based on equation [3]. α_0 is determined in the model for each jurisdiction and each year based on current and historical data on EV sales and the EV fraction of the vehicle stock, which are obtained from Natural Resources Canada (2023), projected forward on the assumption of a steady increase in the base case EV share of new vehicle sales, which ranges from a low of 11 percent in the Maritimes and the prairies to a high of 46 percent in Quebec as of 2050.[3] In 2030 the mandate is assumed to require EVs to take a market share averaging about 49% greater than they would otherwise have. On its own this would require a 54.6% increase in the price of ICEV's to induce the change. But if costs are falling such that parity will be achieved by 2035 the premium is only 17.1%, and if costs are falling toward parity at 2050 the premium is 35.2%.[4] In each case the entirety of the premium accrues as pure rent on ICEVs, though as noted the rents may be partially or entirely captured by EV manufacturers. As long as the constraint binds ($\alpha_t > \alpha_0$) an ICEV price increase of some magnitude is needed, but for a fixed mandate, due to the assumption of declining production costs the increment shrinks over time. Also, after 2035 since ICEVs are banned the rents likewise vanish.

In effect the EV mandate sets up a race between the policy of forcing a growing fraction of buyers to choose something other than what they prefer and the pace of cost reduction in EV production that would lead them to being indifferent. Pushing the EV sales requirements before the cost reductions have been realized will prove to be extremely costly since the price markup applies

[3] Bear in mind the mandate covers not only small passenger cars but also large sedans, SUVs and pickups.

[4] These illustrative figures are not exact because they are based on an unweighted national average EV mandate gap. In the model the exact price factor is computed within each jurisdiction.

across the car market. At present the mere prospect of ICEV rents appears to be inducing many automobile manufacturers to develop EV product lines even though they are unprofitable. As we will see, this may not suffice to prevent the auto sector from bankruptcy, but in subgame sense attempting to capture ICEV rents through EV production is likely better than sticking with ICEV production only.

The EV sales mandate is assumed to follow the announcement in Canada (2022). It begins in 2026 with the requirement that 20 percent of passenger vehicle sales (including SUVs and pickup trucks) must be EVs, then in 2030 the requirement increases to 60 percent followed by 100 percent as of 2035. According to Statistics Canada (2023) the passenger vehicles covered by the mandate make up about 89% of registered vehicles in Canada (excluding trailers) over the 2015-2019 interval so it is assumed that the mandate does not apply to 11 percent of the annual sales of the Canadian automobile sector. The phase-in of the mandate is smoothed in the simulations in part because market participants may engage in credit banking to smooth out their own costs and also to make the diagrams easier to read.

The date at which quality-equivalent cost parity between EVs and ICEVs is achieved turns out to be highly influential on the simulation results. Since it is an unknown parameter we will herein examine two arbitrarily-selected options: 2035 and 2050. The former can be considered the most optimistic case. In effect it proposes that by 2035, when the full mandate is to go into effect it is entirely unnecessary because purchasers of any class of passenger ICEVs will have EV options which they deem to be perfect substitutes and if obliged to select would readily do so with no price inducement necessary. Even assuming that cost parity can be achieved by 2050 is somewhat optimistic since it would require an enormous change in the refueling infrastructure across North

America as well as development of EV options that to date have proven infeasible, such as electric pickup trucks with cold weather range and towing capabilities to rival eight cylinder ICEVs.

4 SIMULATION RESULTS

4.1 COST PARITY AT 2035

The model is trained on data over the 2014 to 2018 interval. For the 2019 economic outcome the model takes in estimates of population, prices, tax rates, government spending levels and other model parameters and solves for an economic equilibrium. The predicted 2019 Canadian auto sector operating surplus is $4.9 billion. 2019 input-output tables are now available and report an observed Canadian operating surplus of $4.5 billion, providing some evidence of reasonable model performance. Figure 2 shows the sequence of model-predicted after-tax operating surpluses of the Canadian automobile sector from 2024 to 2050 assuming EV/ICEV cost parity is achieved in 2035. The dash-dot line shows the base (no-policy) projection of the auto sector operating surplus, which is about $5.5 billion in 2024 and reaches $18.3 billion in 2050. Imposition of a 20% EV sales mandate in 2026 requires a price increase that reduces auto sector earnings gross of ICEV rents from $6.0b to -$8.5b but generates ICEV rents of $11.6b resulting in net earnings of $3.1b, a 50% drop compared to the base case. By 2030 the operating surplus gross of rents has fallen to -$26.7b and the ICEV rents are $13.2b yielding net losses of $13.5b. Throughout the implementation of the EV mandate despite the generation of rents on ICEV sales from 2026 to 2035 the auto sector always loses money relative to the base case and experiences absolute losses from 2027 to 2034. From

2025 to 2050 the losses in the auto sector relative to the base case add up to $131b, assuming the sector never shuts down.[5]

Figures 3—6 summarize changes over time in some key macroeconomic indicators at the national level. Figure 3 shows that relative real GDP actually increases slightly in the first two years of the mandate before dropping below unity after 2028. This is due to a sudden drop in imports beginning in 2026, not to an increase in domestic output. Consumer Utility and Real Industrial Output both decline while GDP temporarily rises (not shown). Table 2 summarizes the sequence of changes in somewhat more detail. The first group shows results for Canada and each jurisdiction for 2030. For the other years (2035, 2040, 2050) only the results for Canada and regionally-representative provinces are shown, for brevity. By 2030 real GDP has gone below the baseline level mirroring the change in output and utility. Figure 4 shows that the cost of the mandate per worker, measured as real earnings per employed person, briefly goes negative before rising to a peak of about $1400 by 2032, falling thereafter to zero. Table 2 and Figures 2-5 show that, according to the model, once cost parity is achieved and the mandate no longer binds, real output returns to its baseline levels, indicating that the policy has only a temporary negative impact, although this may be an artefact of the way fixed capital formation responses are dampened in the

[5] The model does not contain a provision requiring a sector to shut down even under permanent losses. It experiences negative investment depending on Tobin's q, but it continues to operate. To add a shutdown provision would require either including perfect foresight or an *ad hoc* rule prescribing shutdown after an arbitrary accumulation of losses, however these modifications would not add insight beyond the obvious point that eventually a money-losing sector will shut down.

model. Table 2 also shows that a small permanent substitution away from automobiles occurs, and real earnings and utility remain permanently below the baseline in most provinces. Figure 5 indicates that the employment impact of the mandate peaks at a loss of about 34,000 jobs in 2031 but labour demand recovers to baseline levels after 2035.

Demand for motor vehicles drops by 4.5 percent nationally compared to baseline as of 2030, driven by increases in the purchase price of cars that range from 13 to 18 percent depending on the province. Note that the car markets in each province are assumed to be separate. Since baseline EV sales are much higher in Quebec than, for instance, Saskatchewan, the ICEV price increase in Saskatchewan is higher. In the real economy it could be expected that interprovincial shipments of vehicles would to some extent dampen the price differences, but this mechanism is not represented in the model.

Finally Figure 6 shows that greenhouse gas (GHG) emissions do not fall by much. As of 2032 they are only 1.3% below the baseline level (about 7.8 megatonnes CO2 equivalent), then they return to a new path positioned only 1.0% below the baseline. It should be remembered that the mandate only affects the purchase of new passenger vehicles, and even as of 2050 many ICEVs remain on the road. Also, the higher the fraction of EVs in a province, the more demand for gasoline declines which pushes down the market price, prompting a rebound effect in which ICEV drivers can afford to drive more. Rivers and Wigle (2018) used a different modeling framework and found an EV mandate would likewise achieve short run GHG emission reductions of only about 7 megatonnes at a cost of over $1,200 per tonne. By contrast the deadweight economic costs in this model simulation are over $2,700 per tonne.

4.2 COST PARITY AT 2050

The transition costs of the EV mandate under the 2035 parity assumption are large, especially the peak cost per worker of over $1,000 annually in the early 2030s, but the economy returns to baseline by 2035 and it might be reasonable to suppose that the temporary costs would not prohibit implementation of the policy. At the same time, the key assumption in the previous section is that technology will change so quickly the policy is not actually needed. In this section we extend the interval to cost parity another 15 years, so that it takes until 2050 for the market to advance to the point where consumers across all vehicle classes are perfectly indifferent between EVs and ICEVs. Figure 7 shows the results for the auto sector. Again, despite large rents accruing to the ICEV part of the market over the 2026-2035 interval, earnings net of rents go below baseline earnings right away and stay below until 2050. Moreover earnings are negative until 2049 and the losses are very large. By 2030 gross earnings are -$57b, ICEV rents are $24.5b and net losses are $32.5b. Net losses peak in 2035 at $82.9b. Over the 2025 to 2050 interval the auto sector loses just over $1.2 trillion relative to baseline earnings. As noted above the model does not include a shutdown mechanism for a sector enduring permanent losses but in this case it is safe to assume that the EV mandate would lead to the permanent closure of the Canadian auto sector, likely by the early 2030s.

These are large deviations from the historical financial conditions in the auto sector, however it should also be noted that the proposed policy imposes a very large deviation in operations: banning one of the most popular consumer products of all time, the manufacture of which is a major component of modern industrial activity and final consumer demand, while imposing a requirement to purchase instead a product that to date has only received limited consumer approval even with substantial consumer subsidies ($5,000 per unit in the case of Canada in addition to provincial grants and extensive subsidies for charging stations, see Canada 2022). The severe dislocation of the auto sector gives rise to equally severe effects on the rest of the economy, as shown in Figures 3—6 and Table 3. Relative real GDP drops to 7.0% below the baseline as of 2035. In absolute terms although the economy continues to grow, it does so much more slowly. As Table 2 indicates the relative loss of output is most severe in Ontario (13.9%) where most of the Canadian auto sector is located. Indicators are negative across the board as of 2035: Real Industrial Output (-2.4%), Real Earnings per Worker (-6.5%), returns to capital (-15.1%), household demand for cars (-10.3%) and Utility (-0.7%). In all cases the impacts in Ontario are largest. GHG emissions fall by more (-3.2%) in this case largely because of the slowdown in economic activity. Figures 3—5 show that the economy eventually returns to trend over the 2035-2050 interval, and GHG emissions likewise converge back towards the baseline level.

The macroeconomic consequences in this scenario are sufficiently harsh that it is not likely the policy could be maintained as proposed. For instance as of 2035 the EV mandate will have caused a drop in employment of about 140,000 jobs and a cost per employed person reaching nearly $7,000. Moreover it accomplishes very little towards the stated goal of reducing GHG emissions. As of 2035 emissions are only 3.2% below the baseline, at a cost of nearly $4,700 per tonne. The overall implication of this simulation is that even if the cost of EV manufacturing declines at such a rate that parity with ICEVs on a quality-equivalent basis across all passenger vehicle types is achieved by 2050, this will still not be fast enough to make a 2035 EV mandate economically feasible.

5 CONCLUSIONS

The phase-in of an EV sales mandate forces a reduction in ICEV sales which creates an opportunity for automakers to earn rents on conventional cars. At the same time the market for cars in general will shrink until such time as EVs can be produced at cost parity with ICEVs, taking into account not only the cost of manufacturing basic electric vehicles themselves but also matching power and range characteristics of all classes of ICEVs and providing fast charging infrastructure of comparable convenience to the current availability of fuel stations. If the EV mandate is phased in faster than cost-parity can be achieved the rents on ICEVs will not suffice to offset the losses in auto sector revenue. Simulations in a large-scale numerical general equilibrium model of the Canadian economy trained on provincial-level input-output data over 2014-2018 suggests that moving to a 100 percent EV sales mandate by 2035 will move the automotive sector into a loss position in the early 2030s. The severity of the losses and the overall macroeconomic consequences depend on assumptions about the speed of technical progress in the EV sector. Put simply, the mandate is potentially affordable only if it is also unnecessary. If EV production technology improves so quickly that cost parity is achieved by 2035, there will be some large temporary transition costs but the economy will return to baseline after 2035. If full cost parity does not happen until 2050, which is still an optimistic time horizon with regards to larger utility vehicles essential in many Canadian regions, a 2035 EV mandate will have sufficiently large negative consequences that it will effectively destroy the Canadian auto industry and will cause widespread economic losses elsewhere. It is not plausible in this case that the policy would be sustainable.

The pace of achieving cost parity is partly constrained by technological progress and also, to some extent, by geopolitical factors including China's market power over NdFeB magnet production. To the extent governments try to mandate a switch from ICEVs to EVs faster than technology and prices permit they need to be aware of the likelihood of causing substantial economic losses.

The analysis herein provides some insight into why automakers appear willing to build EV product lines even though they have long lost money on them and expect to continue to do so. If imposition of an EV mandate is a credible threat and the policies are structured in such a way that manufacturers on the EV side of the market can capture most or all the ICEV rents then the worst scenario for an automaker is to be focused solely on ICEV production. Not only will the product be banned in just over a decade, but there will be no prospect for rent capture during the phase-in, and earnings gross of rents are always below earnings net of rents. However this strategy is only advantageous in a subgame sense: given the inevitability of an EV mandate it is better to produce EVs than not, even if they are not profitable, at least up to a point. But more generally it would be better for the auto sector as a whole, and the economy too, to wait until EVs achieve something close to cost parity with ICEVs before attempting a sales mandate. Implementing a mandate on a schedule that outpaces achievement of cost parity risks the destruction of the auto sector in its entirety as well as substantial losses to the rest of the economy.

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8 FIGURES

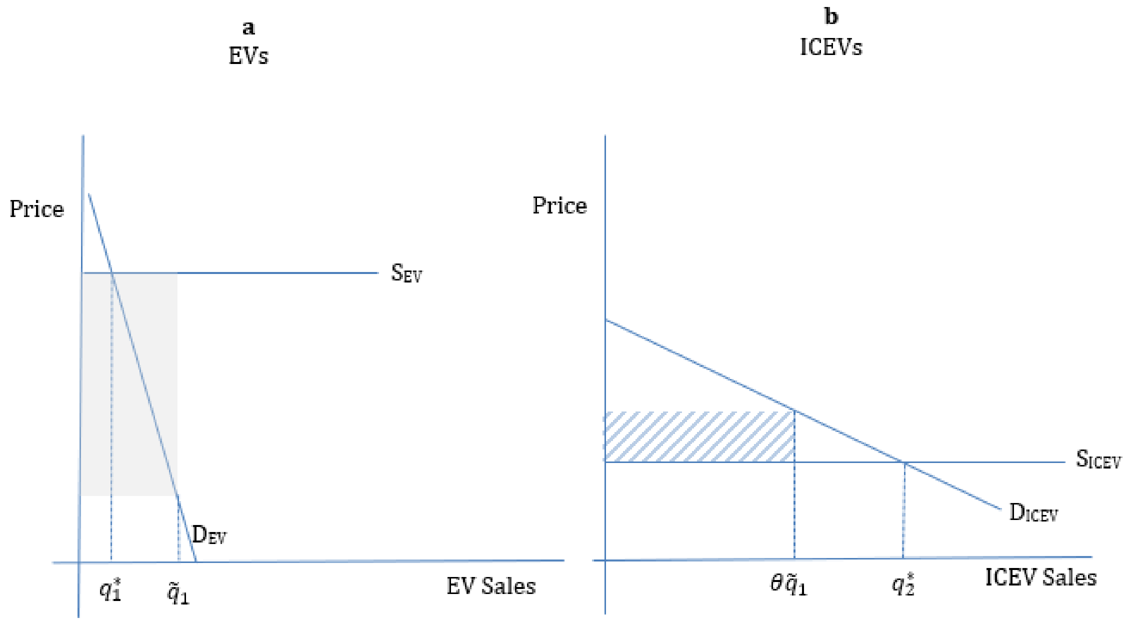

Figure 1. Simultaneous EV and ICEV markets with EV sales mandate.

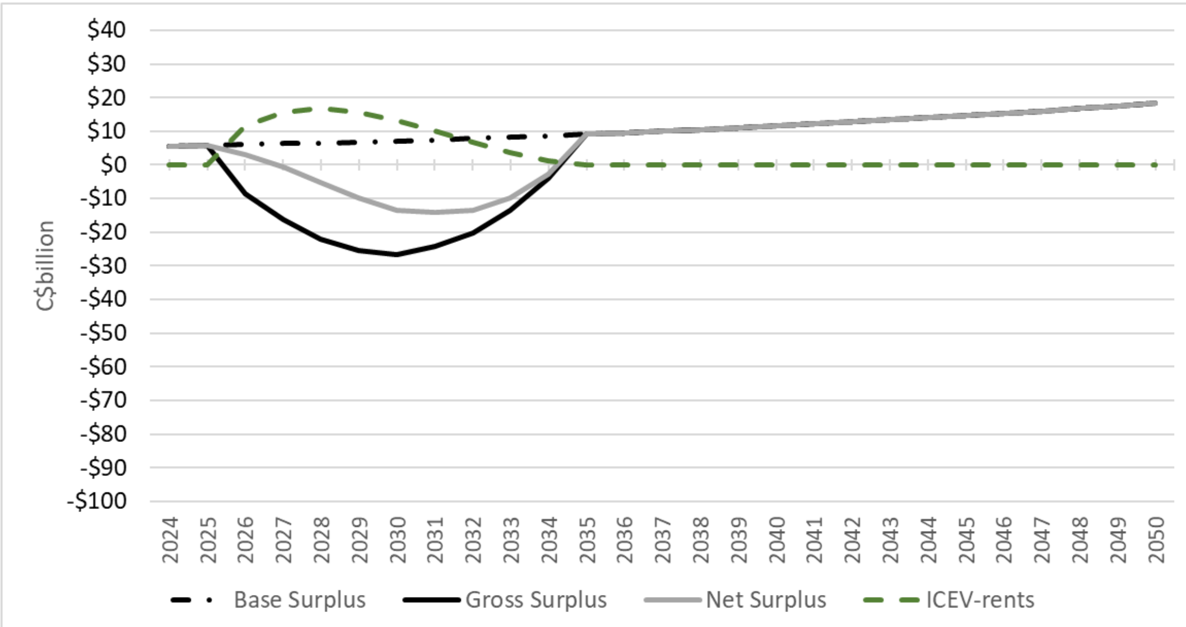

Figure 2: Base case earnings and earnings paths under EV mandate assuming cost parity by 2035. Net Surplus denotes Gross Surplus plus ICEV Rents.

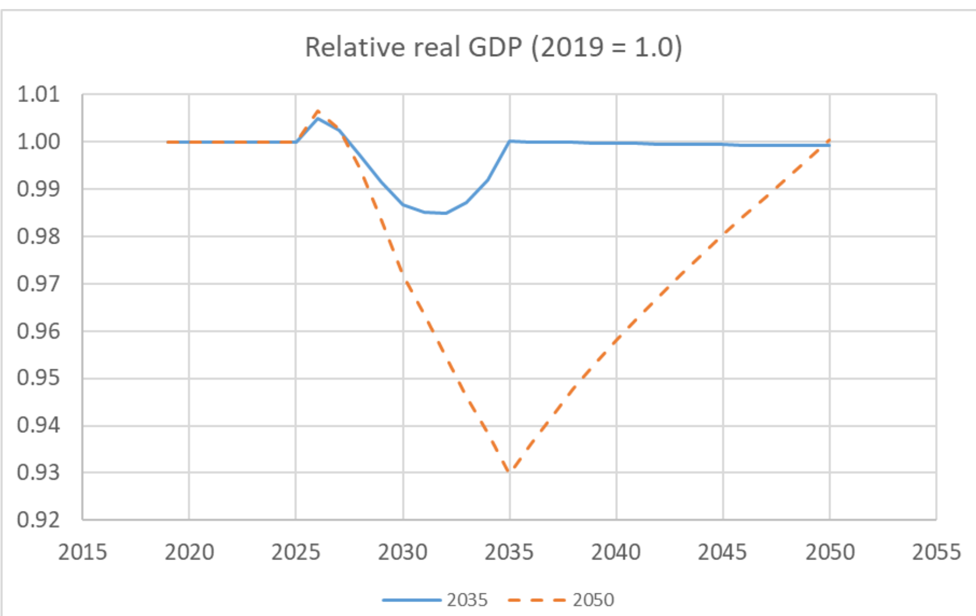

Figure 3. GDP under the EV mandate relative to baseline, 2019—2050 assuming cost parity by year indicated.

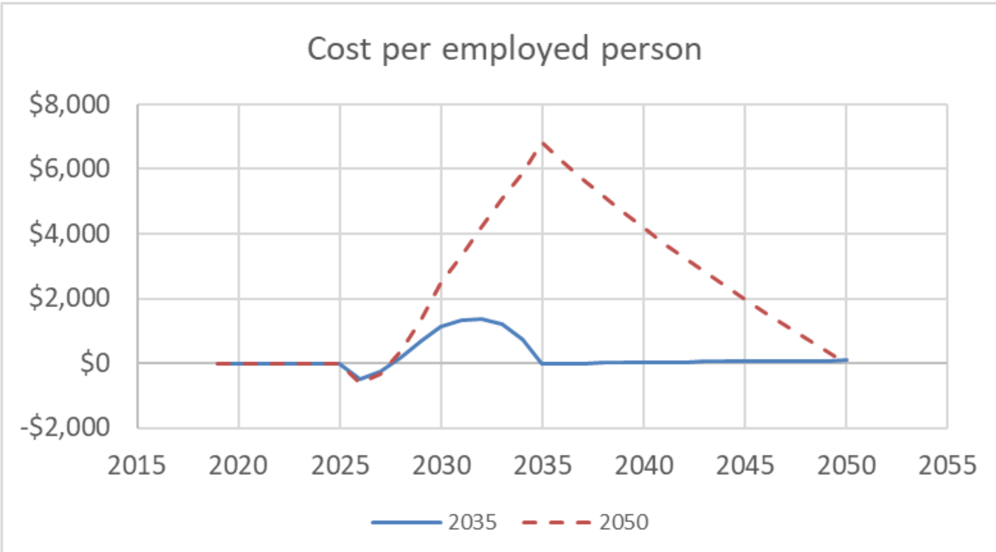

Figure 4. Cost per employed person (national, $CAD) of the EV mandate assuming cost parity by year indicated.

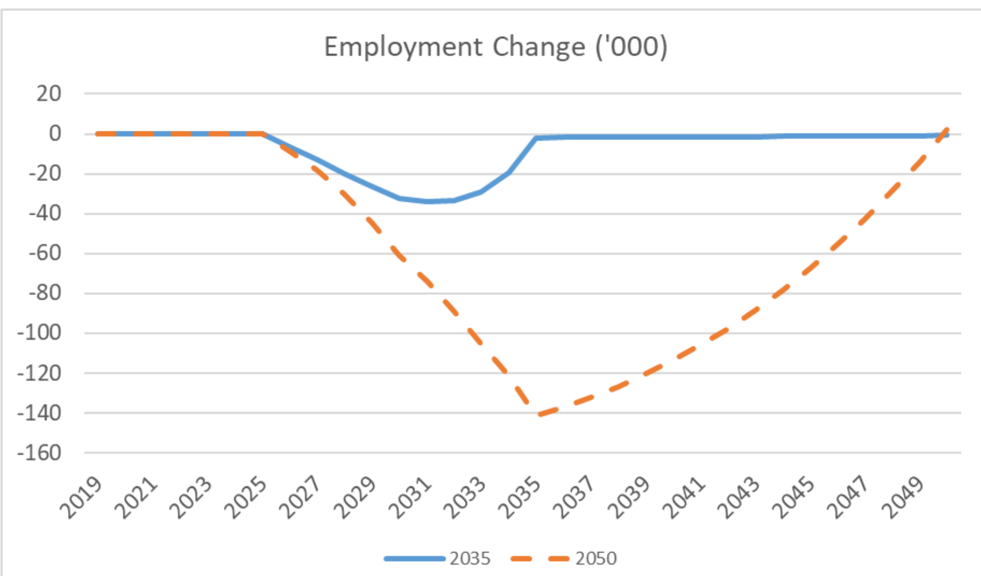

Figure 5. Change in total employment nationally under the EV mandate assuming cost parity by year indicated.

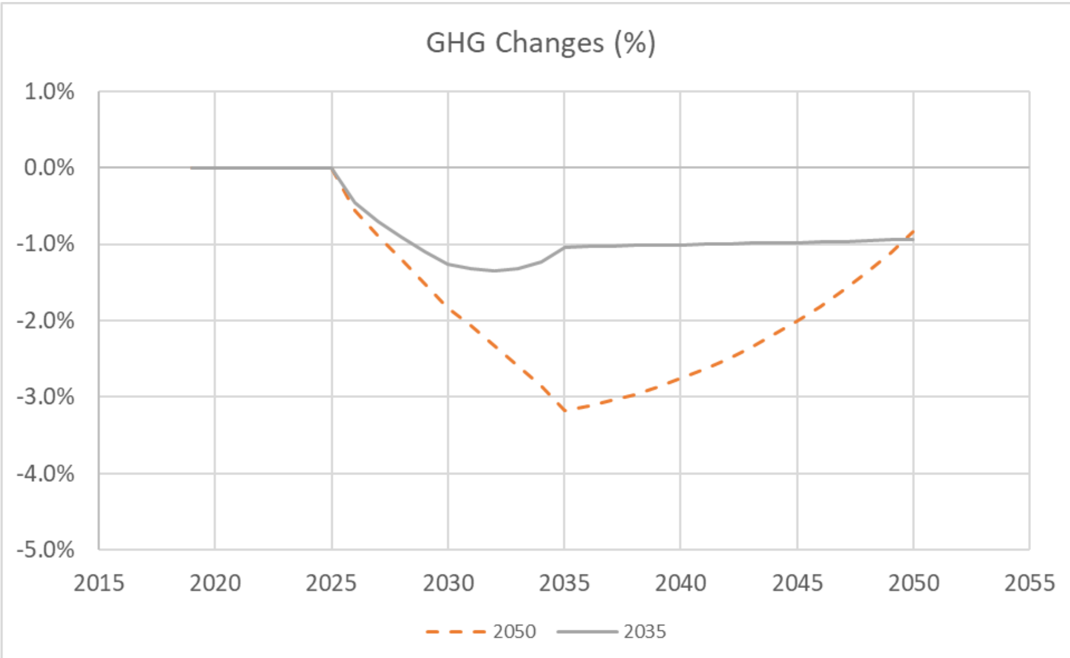

Figure 6. Percent change in national GHG emissions under the EV mandate assuming cost parity by year indicated.

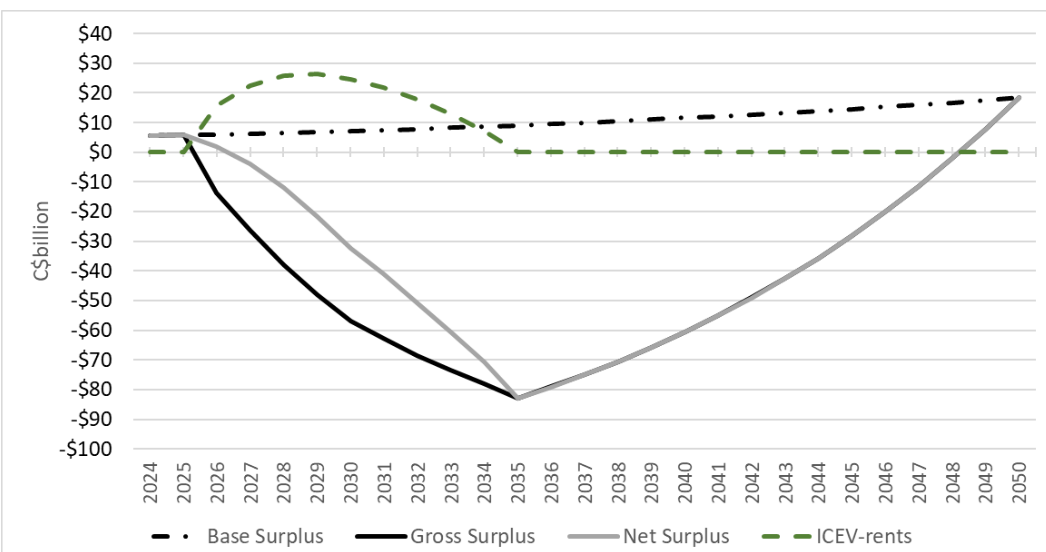

Figure 7: Base case earnings and earnings paths under EV mandate assuming cost parity by 2050.

9 TABLES

	Average Mandate Size	Markup Factor 2035	Markup Factor 2050
2019	0.000	1.000	1.000
2020	0.000	1.000	1.000
2021	0.000	1.000	1.000
2022	0.000	1.000	1.000
2023	0.000	1.000	1.000
2024	0.000	1.000	1.000
2025	0.000	1.000	1.000
2026	0.151	1.095	1.130
2027	0.238	1.132	1.196
2028	0.324	1.157	1.255
2029	0.409	1.171	1.308
2030	0.491	1.171	1.352
2031	0.551	1.153	1.375
2032	0.615	1.128	1.396
2033	0.678	1.094	1.413
2034	0.742	1.052	1.425
2035	0.815	1.000	1.438
2036	0.809	1.000	1.406
2037	0.803	1.000	1.374
2038	0.796	1.000	1.343
2039	0.790	1.000	1.311
2040	0.784	1.000	1.281
2041	0.777	1.000	1.251
2042	0.771	1.000	1.221
2043	0.765	1.000	1.192
2044	0.758	1.000	1.163
2045	0.752	1.000	1.135
2046	0.745	1.000	1.107
2047	0.739	1.000	1.079
2048	0.733	1.000	1.053
2049	0.726	1.000	1.026
2050	0.720	1.000	1.000

Table 1. Average price markup factor. Column 1: unweighted national average mandate gap. Column 2: Price adjustment factor assuming cost parity achieved in 2035. Column 3: same but for parity year 2050.

	Real GDP	Real Industrial Output	Real Earnings per Worker	Capital Returns rel. to avg.	HH Auto Demand	Utility	GHG Emissions
	2030						
Canada	**-1.3**	**-0.8**	**-1.2**	**-3.3**	**-4.5**	**-0.2**	**-1.3**
BC	-1.1	-0.3	-1.2	-1.6	-2.4	-0.1	-0.6
Alberta	-0.6	-0.3	-0.7	-1.7	-2.5	-0.1	-0.6
Saskatchewan	-0.6	-0.4	-0.6	-2.2	-5.1	-0.2	-0.7
Manitoba	-1.3	-0.5	-1.3	-3.4	-5.7	-0.2	-1.5
Ontario	-2.8	-1.6	-2.4	-4.9	-6.5	-0.3	-2.2
Quebec	-1.2	-0.7	-1.1	-3.1	-4.6	-0.1	-1.2
New Brunswick	-0.5	-0.4	-0.5	-6.7	-2.2	-0.1	-2.0
Nova Scotia	-1.3	-0.6	-1.3	-3.8	-5.6	-0.2	-1.8
PEI	-0.4	-0.1	-0.5	-4.3	-0.4	-0.1	-1.4
Newfoundland	-0.7	-0.1	-0.7	-2.2	-3.2	-0.1	-0.8
Far North	-0.4	0.0	-0.6	-2.4	-0.5	0.0	-0.8
	2035						
Canada	**0.0**	**-0.1**	**0.0**	**-0.1**	**-0.3**	**-0.1**	**-1.0**
BC	0.0	-0.1	0.0	-0.1	-0.3	-0.1	-0.6
Alberta	-0.1	-0.1	-0.1	-0.1	-0.2	0.0	-0.7
Ontario	0.1	-0.1	0.1	0.0	-0.3	0.0	-1.3
Quebec	0.1	-0.1	0.1	-0.1	-0.3	-0.1	-1.1
Newfoundland	-0.1	0.0	-0.1	-0.3	-0.2	-0.1	-1.1
	2040						
Canada	**0.0**	**0.0**	**0.0**	**-0.1**	**-0.3**	**-0.1**	**-1.0**
BC	0.0	0.0	0.0	-0.1	-0.3	-0.1	-0.6
Alberta	-0.1	-0.1	-0.1	-0.1	-0.2	0.0	-0.7
Ontario	0.0	0.0	0.0	-0.1	-0.3	0.0	-1.2
Quebec	0.0	0.0	0.0	0.0	-0.3	-0.1	-1.0
Newfoundland	-0.1	0.0	-0.1	-0.3	-0.2	-0.1	-1.1
	2050						
Canada	**-0.1**	**0.0**	**-0.1**	**0.0**	**-0.2**	**-0.1**	**-0.9**
BC	-0.1	0.0	-0.1	0.0	-0.3	-0.1	-0.6
Alberta	-0.1	-0.1	-0.1	0.0	-0.1	0.0	-0.7
Ontario	-0.1	0.0	-0.1	-0.1	-0.3	-0.1	-1.1
Quebec	0.0	0.0	0.0	0.0	-0.2	-0.1	-0.7
Newfoundland	-0.1	0.0	-0.1	-0.4	-0.2	-0.1	-1.2

Table 2: Summary of macroeconomic effects of EV mandate 2030–2050 assuming quality-equivalent EV production cost parity by 2035.

	Real GDP	Real Industrial Output	Real Earnings per Worker	Capital Returns rel. to avg.	HH Auto Demand	Utility	GHG Emissions
	2030						
Canada	**-2.8**	**-1.4**	**-2.5**	**-6.3**	**-8.5**	**-0.3**	**-1.8**
BC	-2.5	-0.5	-2.6	-3.1	-4.6	-0.1	-0.8
Alberta	-1.3	-0.5	-1.4	-3.4	-4.8	-0.2	-0.9
Saskatchewan	-1.2	-0.6	-1.1	-4.2	-9.5	-0.3	-1.0
Manitoba	-2.8	-1.0	-2.7	-6.4	-10.6	-0.3	-2.1
Ontario	-5.9	-2.9	-5.2	-9.3	-12.1	-0.5	-3.5
Quebec	-2.6	-1.3	-2.5	-6.0	-8.7	-0.2	-1.7
New Brunswick	-0.9	-0.6	-1.1	-13.3	-4.2	-0.2	-2.5
Nova Scotia	-2.6	-1.0	-2.6	-7.2	-10.4	-0.3	-2.4
PEI	-0.7	-0.1	-1.0	-8.7	-0.7	-0.2	-1.7
Newfoundland	-1.3	-0.1	-1.4	-4.2	-6.1	-0.3	-1.0
Far North	-0.8	0.0	-1.2	-4.8	-0.8	-0.1	-0.9
	2035						
Canada	**-7.0**	**-2.4**	**-6.5**	**-15.1**	**-10.3**	**-0.7**	**-3.2**
BC	-7.1	-1.3	-7.1	-7.9	-5.6	-0.3	-1.7
Alberta	-2.8	-0.7	-3.1	-8.1	-5.6	-0.4	-1.4
Ontario	-13.9	-4.8	-12.5	-22.5	-15.6	-1.1	-6.1
Quebec	-6.8	-2.2	-6.4	-14.5	-10.1	-0.4	-2.9
Newfoundland	-2.8	-0.6	-3.0	-10.7	-7.6	-0.6	-2.1
	2040						
Canada	**-4.2**	**-1.9**	**-3.8**	**-12.3**	**-7.0**	**-0.5**	**-2.8**
BC	-4.0	-1.2	-4.0	-6.1	-3.8	-0.2	-1.6
Alberta	-1.8	-0.6	-2.1	-6.4	-4.0	-0.3	-1.3
Ontario	-7.9	-3.7	-6.8	-19.0	-10.8	-0.9	-5.0
Quebec	-3.8	-1.7	-3.6	-11.1	-6.4	-0.3	-2.5
Newfoundland	-1.9	-0.4	-2.0	-8.5	-5.3	-0.5	-1.9
	2050						
Canada	**0.0**	**0.0**	**0.0**	**0.1**	**0.0**	**0.0**	**-0.8**
BC	0.1	0.0	0.1	0.1	0.1	0.0	-0.5
Alberta	0.0	0.0	0.0	0.1	0.0	0.0	-0.7
Ontario	0.1	0.0	0.1	0.0	0.1	0.0	-0.9
Quebec	0.1	0.0	0.1	0.1	0.0	0.0	-0.6
Newfoundland	0.0	0.0	0.0	-0.3	0.0	0.0	-1.2

Table 3: Summary of macroeconomic effects of EV mandate 2030–2050 assuming quality-equivalent EV production cost parity by 2050.

APPENDIX

Within each province or territory the model identifies inputs and outputs for the following sectors:

1 Agriculture Fishing and Trapping
2 Forestry and Logging
3 Oil Sands
4 Conventional Crude Oil
5 Natural Gas
6 Oil and Gas Support Activities
7 Coal
8 Other Mining
9 Electricity
10 Other Utilities incl Gas Distribution
11 Construction
12 Food Production
13 Semi-durables
14 Refined Fuels
15 Other Petrochemicals
16 Cement and Concrete
17 Automotive Parts and Assembly
18 Other Manufacturing
19 Wholesale and Retail Sales
20 Air Rail & Bus Transportation
21 Gas Pipelines
22 Crude Pipelines
23 Trucking Courier and Storage
24 Media, Banking, Finance, Information and related Professional Services
25 Education and Health
26 Entertainment, Travel, Restaurants and Miscellaneous Services.

The list of commodities is the same and all outputs are assigned to the corresponding sector. Petroleum products are distinguished between fuels and those used for non-combustion applications.

Nesting structure

Households and firms are represented using nested CES share functions. The household nest sequence is as follows. Nesting share elasticity parameter values are indicated in brackets, and where a range is shown they vary across provinces.

<table>
<tr><td>Savings</td><td></td><td></td><td></td></tr>
<tr><td>Leisure</td><td></td><td></td><td></td></tr>
<tr><td rowspan="7">Consumption
(0.3-0.4)</td><td rowspan="3">ENERGY &
TRANSPORT
(0.4-0.5)</td><td>UTILITIES
(0.05)</td><td>Electricity
Other Utilities
Gas Pipeline Services</td></tr>
<tr><td>FUELS
(0.1)</td><td>Natural Gas
Coal
Gasoline
Petrochemicals</td></tr>
<tr><td>TRANSPORT
(0.05-0.3)</td><td>Oil Pipeline Services
Air, Rail & Bus
Trucking & Storage</td></tr>
<tr><td rowspan="2">GOODS
(0.6)</td><td>BASIC GOODS
(0.4)</td><td>Conventional Crude
Oil Sands
Agriculture
Forest Products
Mining</td></tr>
<tr><td>PRODUCED GOODS
(0.7)</td><td>Cement
Semi-durables
Auto Parts & Assembly
Other Manufacturing
Food</td></tr>
<tr><td rowspan="2">SERVICES
(0.5)</td><td>PROFESSIONAL
SERVICES
(0.8)</td><td>Entertainment
Construction
Media, Finance Etc
Sales & Retail</td></tr>
<tr><td>OTHER SERVICES
(0.8)</td><td>Oil & Gas Support
Education & Health</td></tr>
</table>

The value of σ (elasticity of leisure demand with respect to real wage) in equation [2] is -1.2. The labour supply elasticity with respect to the real wage is $-\sigma\theta\left(\frac{w}{p}\right)^{\sigma}/L$ where L is the labour supply. This changes as wages, prices and L change. The uncompensated own-price labour supply elasticity is computed in the model solution and is typically around 0.5 or 0.6.

The nesting structure for firms is essentially the same except: the elasticity on the FUELS nest is 0.01 while that on the TRANSPORT nest is 0.4-0.6, that on both OTHER SERVICES and SERVICES is 0.1, on the top level of intermediate inputs it is 0.6 and on the top level which combines intermediate inputs with labour and capital demand it is 0.75-0.95. The return to capital is the surplus after labour and intermediate inputs are paid.