Online Appendices For "The electric vehicle transition and the economics of banning gasoline vehicles"

Stephen P. Holland* Erin T. Mansur† Andrew J. Yates‡

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*Department of Economics, University of North Carolina at Greensboro and NBER. Mailing Address: Bryan School of Business and Economics, Department of Economics, Bryan 462, PO Box 26170, Greensboro, NC 27402-6170. Phone: 336-334-5463. Fax: 336-334-5580. Email: sphollan@uncg.edu

†Tuck School of Business at Dartmouth and NBER. Mailing Address: 100 Tuck Hall, Dartmouth College, Hanover, NH 03755-3514. Email: erin.mansur@dartmouth.edu

‡Department of Economics and Environment, Ecology, and Energy Program, University of North Carolina at Chapel Hill. Mailing Address: Department of Economics, University of North Carolina Chapel Hill, CB 3305 University of North Carolina Chapel Hill, NC 27599. Email: ajyates@email.unc.edu.

A Planners Problem

This appendix derives the necessary conditions for the planner's problem in (1). We consider a finite horizon version of the planner's problem with terminal time T and salvage values. Taking the limit as T goes to infinity characterizes the infinite horizon problem. With salvage value of a gasoline vehicle c_g and an electric vehicle $\hat{c}_x$ (in current value), the finite horizon planner's problem is

$$\begin{aligned}
\max_{g,x} \quad & c_g e^{-rT} G(T) + \hat{c}_x e^{-rT} X(T) + \int_0^T e^{-rt} \left(U(G,X) - c_g g - c_x x - \delta_g G - \delta_x X \right) dt \\
\text{s.t.} \quad \dot{G} &= -aG + g \; ; \; G(0) = G^{ss} \\
\dot{X} &= -aX + x \; ; \; X(0) = 0 \\
g &\geq 0, \\
x &\geq 0
\end{aligned}$$

where G^{ss} is the initial steady state stock of gasoline vehicles.

Let $\tilde{\alpha}$ and $\tilde{\beta}$ be the adjoint variables corresponding to the state equations for G and X. The Hamiltonian is

$$H = \tilde{\alpha}(-aG + g) + \tilde{\beta}(-aX + x) + e^{-rt} \left(U(G,X) - c_g g - c_x x - \delta_g G - \delta_x X \right).$$

From the Maximum Principle[1] the necessary conditions for the optimal control are the state equations, the initial conditions, and

$$\begin{aligned}
-\dot{\tilde{\alpha}} + \tilde{\alpha} a - e^{-rt} \left(U_G - \delta_g \right) &= 0 && \text{(adjoint equations)} \\
-\dot{\tilde{\beta}} + \tilde{\beta} a - e^{-rt} \left(U_X - \delta_x \right) &= 0 \\
\tilde{\alpha}(T) &= c_g e^{-rT} && \text{(adjoint final conditions)} \\
\tilde{\beta}(T) &= \hat{c}_x e^{-rT},
\end{aligned}$$

In addition, the controls g and x must maximize the Hamiltonian subject to the nonnegativity constraints. Because the Hamiltonian is linear in the controls, we use the Kuhn-Tucker

[1] See for example Kamien and Schwartz (2012).

necessary conditions for the controls:

$$g \geq 0 \quad \tilde{\alpha} - e^{-rt}c_g \leq 0 \quad (\tilde{\alpha} - e^{-rt}c_g)g = 0 \quad \text{(necessary condition for } g)$$
$$x \geq 0 \quad \tilde{\beta} - e^{-rt}c_x \leq 0 \quad (\tilde{\beta} - e^{-rt}c_x)x = 0 \quad \text{(necessary condition for } x)$$

Using the change of variables $\alpha = e^{rt}\tilde{\alpha}$ and $\beta = e^{rt}\tilde{\beta}$ (i.e. current values instead of present values) the adjoint equations become

$$\dot{\alpha} = (a + r)\alpha - U_G + \delta_g \;; \alpha(T) = c_g.$$

$$\dot{\beta} = (a + r)\beta - U_X + \delta_x \;; \beta(T) = c_x$$

The necessary conditions for interior g and x become

$$g \geq 0 \quad \alpha - c_g \leq 0 \quad (\alpha - c_g)g = 0 \quad \text{(necessary condition for } g)$$
$$x \geq 0 \quad \beta - c_x \leq 0 \quad (\beta - c_x)x = 0 \quad \text{(necessary condition for } x)$$

B Proofs of Propositions 1-2

Before proving Propositions 1-2, we state and prove the following lemma, which allows us to solve for the adjoint variable for gasoline vehicles from the adjoint equation:

Lemma 2. *The adjoint equation (3) for gasoline vehicles is solved by the function*

$$\alpha(t) = e^{(a+r)t}\left[\int_{t_0}^{t} e^{-(a+r)\tau}[\delta_g - U_G(G(\tau), X(\tau)]d\tau + K\right] \tag{A-1}$$

for an arbitrary constant K.

With an initial condition $\alpha(t_0) = \alpha_0$, the adjoint equation is solved by

$$\alpha(t) = e^{(a+r)t}\left[\int_{t_0}^{t} e^{-(a+r)\tau}[\delta_g - U_G(G(\tau), X(\tau))]d\tau + \alpha_0 e^{-(a+r)t_0}\right] \tag{A-2}$$

With a terminal condition, the adjoint equation is solved by

$$\alpha(t) = e^{(a+r)t}\int_{t}^{\infty} e^{-(a+r)\tau}[U_G(G(\tau), X(\tau)) - \delta_g]d\tau. \tag{A-3}$$

Proof. The adjoint equation (3) is a first-order differential equation of the form

$$\dot{\alpha} - (a + r)\alpha = f(t)$$

where $f(t) = \delta_g - U_G(G(t), X(t))$ is a function of t. Using the integrating factor method, the solution to a differential equation of this form, which can be easily verified, is

$$\alpha(t) = e^{(a+r)t}\left[\int_{t_0}^{t} e^{-(a+r)\tau} f(\tau)d\tau + K\right],$$

where K is an arbitrary constant.

If $\alpha(t_0) = \alpha_0$, we set (A-1) equal to α_0 and solve for K, which implies $K = \alpha_0 e^{-(a+r)t_0}$. Substitution in (A-1) yields (A-2).

For the terminal condition, instead of using the transversality conditions, we use the terminal condition $\alpha(T) = \alpha_1$ with an arbitrary end period T. We then determine the constant K_T with this arbitrary end period and take the limit of K_T as $T \to \infty$. With this terminal condition in (A-1) we can solve for K_T which yields

$$K_T = \alpha_1 e^{-(a+r)T} - \int_{t_0}^{T} e^{-(a+r)\tau}[\delta_g - U_G(G(\tau), X(\tau))]d\tau.$$

We then take the limit as $T \to \infty$ of K_T and substitute the result into (A-1) which gives

$$\alpha(t) = e^{(a+r)t}\left[\int_{t_0}^{t} e^{-(a+r)\tau}[\delta_g - U_G(G(\tau), X(\tau)]d\tau - \int_{t_0}^{\infty} e^{-(a+r)\tau}[\delta_g - U_G(G(\tau), X(\tau))]d\tau\right]$$

which simplifies to (A-3). Note that the solution does not depend on the arbitrary constant α_1. □

Proof of Proposition 1

Proof. To prove the condition for banning gasoline vehicles, we show that the solution satisfies the first order conditions with $g^\infty = 0$. As $t \to \infty$, if $g = 0$ and x is such that (5) is satisfied, then for some T_1 we have $(G, X) \approx (0, X^*)$. We can then evaluate the adjoint variable using (A-3) from Lemma 2, which shows that for $t > T_1$

$$\alpha(t) = e^{(a+r)t} \int_t^\infty e^{-(a+r)\tau}[U_G(G(\tau), X(\tau)) - \delta_g]d\tau.$$

$$\approx e^{(a+r)t} \int_t^\infty e^{-(a+r)\tau}[U_G(0, X^*) - \delta_g]d\tau.$$

$$= (U_G(0, X^*) - \delta_g)/(a+r) < c_g$$

which implies $\alpha(t) < c_g$. Together with $g = 0$, the remaining first order condition is satisfied.

A proof by contradiction demonstrates the condition under which gasoline vehicles are not banned. Suppose $g^\infty = 0$ which implies that $g(t) = 0$ for all $t > T_1$ for some T_1. But this implies that for some T_2 with $t > T_2 > T_1$ we have $G \approx 0$ and $X \approx X^*$ so that $U_G(G, X) \approx U_G(0, X^*)$ where $\approx$ means "arbitrarily close to", i.e., within an ϵ-ball. Again using (A-3) from Lemma 2, we have that for $t > T_2$

$$\alpha(t) = e^{(a+r)t} \int_t^\infty e^{-(a+r)\tau}[U_G(G(\tau), X(\tau)) - \delta_g]d\tau.$$

$$\approx e^{(a+r)t} \int_t^\infty e^{-(a+r)\tau}[U_G(0, X^*) - \delta_g]d\tau.$$

$$= (U_G(0, X^*) - \delta_g)/(a+r) > c_g$$

which contradicts the first order condition $\alpha \leq c_g$.

□

Proof of Proposition 2

Proof. To characterize t^e note that $x > 0$ over the interval $[t^e, t^g]$ so (5) must hold including at t^e. But at t^e we have $G(t^e) = G^{ss}$ and $X(t^e) = 0$. Substituting these into (5) $U_X(G^{ss}, 0) = (a+r)c_x(t^e) + \delta_x(t^e) + \dot{c}_x(t^e)$ which can then be solved for t^e and characterizes t^e. (7) follows directly.

To characterize t^g, we focus on the adjoint variable α. During $[t^e, t^g]$, we have g interior, so that $\alpha = c_g$. After t_g, α evolves according to the adjoint equation (3) which we can solve using (A-3) from Lemma 2 to have

$$\alpha(t) = e^{(a+r)t} \int_t^\infty e^{-(a+r)\tau} [U_G(G^{sim}(\tau), X^{sim}(\tau)) - \delta_g] d\tau. \tag{A-4}$$

But at t^g, we have $\alpha(t^g) = c_g$ which implies the result

$$c_g = \int_{t^g}^\infty e^{-(a+r)(\tau - t^g)} (U_G(G^{sim}(\tau), X^{sim}(\tau)) - \delta_g) d\tau.$$

□

C Analysis of Gap Solution

The gap solution is characterized first by gasoline vehicle production, then by no vehicle production (the gap) and finally by electric vehicle production. During $[0, t^g]$, gasoline vehicles are produced in steady state with gasoline stock equal to G^{ss} and interior gasoline production $g = aG^{ss} > 0$. At time t^g, production of gasoline vehicles stops and from then on, the stock of gasoline vehicles decreases exponentially so $G(t) = G^{ss}e^{-a(t-t^g)}$ for all $t > t^g$. At time t^e, production of electric vehicles starts with interior x determined so that X satisfies (5) with $G(t) = G^{ss}e^{-a(t-t^g)}$.

The next proposition characterizes the transition times t^e and t^g in the gap solution. In this case, the transition times must be solved for jointly.

Proposition 4. *In the gap solution, the transition times t^e and t^g are the solutions to the system of equations described by*

$$U_X(G^{ss}e^{-a(t^e - t^g)}, 0) = (a + r)c_x(t^e) + \delta_x(t^e) - \dot{c}_x(t^e) \tag{A-5}$$

and

$$c_g = \int_{t^g}^{t^e} e^{-(a+r)(\tau - t^g)} (U_G(G^{ss}e^{-a(\tau - t^g)}, 0) - \delta_g) d\tau + \int_{t^e}^\infty e^{-(a+r)(\tau - t^g)} \left[U_G(G^{ss}e^{-a(\tau - t^g)}, X^{gap}(\tau)) - \delta_g\right] d\tau. \tag{A-6}$$

where $X^{gap}(t)$ satisfies $U_X(G^{ss}e^{-a(t-t^g)}, X^{gap}(t)) = (a + r)c_x + \delta_x - \dot{c}_x$ for all $t > t^e$.

Similar to what we found in the simultaneous solution, (A-5) shows that electric vehicle production begins when the full marginal cost of the electric vehicle falls to the marginal benefit of an electric vehicle. However because of the gap in production, the stock of gasoline vehicles decreases and the marginal benefit of an electric vehicle is higher than the initial steady state value. Thus the gap in production increases the marginal benefit of an electric vehicle and causes their production to begin earlier. Notice that (A-5) is a function of both t^e and t^g so the marginal benefit depends on the stock of gasoline vehicles, which in turn depends on how long it has been since production of these vehicles was stopped. Equation (A-6) shows that at time t^g, the production cost of the vehicle equals the discounted net benefits of an additional gasoline vehicle at each time in the future. This equation is similar to (8) except that it depends on t^e because the production paths and hence the marginal benefit of a gasoline vehicle change when electric vehicle production begins. Thus equations (A-5) and (A-6) each depend on both t^g and t^e.

The gap solution has a period of time in which no vehicles are produced. Because this is counterintuitive, it is useful to point out that the gap solution can occur for reasonable parameterizations of the model. The next proposition shows that the gap solution obtains in the rather important special case in which gasoline and electric vehicles are perfect substitutes.

Proposition 5. *If the benefit function is $U(G, X) = u(G + \eta X)$ with u concave, then the solution to the planner's problem has $t^g < t^e$.*

The perfect substitutes case provides a useful benchmark for the analysis of the transition from gasoline to electric vehicles. The planner accounts for the decreasing damages and production costs of electric vehicles when determining the optimal time to introduce them. If electric vehicles are perfect substitutes for gasoline vehicles, there is no loss in benefit from stoping gasoline vehicle production if they are replaced by electric vehicles. In this case, the planner stops production of gasoline vehicles before beginning production of electric vehicles because gasoline vehicles produced today remain in the fleet for some time, and they will cause more damages than the increasingly clean electric vehicles. In addition, stopping production of gasoline vehicles increases the marginal benefit of an electric vehicle, thus leading to an earlier introduction of electric vehicles.

If vehicles are not perfect substitutes, either the gap or simultaneous solution may occur. Loosely speaking, if electric cars are good substitutes for gasoline vehicles, then the gap solution occurs. If, however, the vehicles are not good substitutes, then the planner accounts for this by extending the production of gasoline vehicles past the point at which electric vehicles are introduced and we have the simultaneous solution.

Proof of Proposition 4

Proof. After t^g, the gasoline vehicle stock is simply $G(t) = G^{ss}e^{-a(t-t^g)}$. So at t^e we have

$$U_X(G^{ss}e^{-a(t^e-t^g)}, 0) = (a+r)c_x(t^e) + \delta_x(t^e) - \dot{c}_x(t^e)$$

This equation is a function of both t^e and t^g, so we need another equation to pin down the transition times.

The other equation comes from the continuity of $\alpha(t)$. For $t \in [0, t^g]$, we have $\alpha(t) = c_g$. For $t \in [t^g, t^e]$ and for $t \in [t^e, \infty]$, $\alpha(t)$ evolves according to two different differential equations, which we can solve using Lemma 2. Continuity at t^e gives the additional equation.

For the interval $[t^g, t^e]$, the adjoint equation can be solved using (A-2) from Lemma 2 with the initial condition $\alpha(t^g) = c_g$ as

$$\alpha(t) = e^{(a+r)t}\left[\int_{t^g}^{t} e^{-(a+r)\tau}[\delta_g - U_G(G^{ss}e^{-a(\tau-t^g)}, 0)]d\tau + c_g e^{-(a+r)t^g}\right] \tag{A-7}$$

for the interval $[t^g, t^e]$

For the interval $[t^e, \infty)$, the adjoint equation can be solved using (A-3) from Lemma 2 as

$$\alpha(t) = e^{(a+r)t}\left[\int_{t}^{\infty} e^{-(a+r)\tau}\left[U_G(G^{ss}e^{-a(\tau-t^g)}, X^{gap}(\tau)) - \delta_g\right]d\tau\right] \tag{A-8}$$

for $t \geq t^e$. Since (A-7) and (A-8) must both hold at t^e, we have the result

$$c_g = \int_{t^g}^{t^e} e^{-(a+r)(\tau-t^g)}(U_G(G^{ss}e^{-a(\tau-t^g)}, 0) - \delta_g)d\tau + \int_{t^e}^{\infty} e^{-(a+r)(\tau-t^g)}\left[U_G(G^{ss}e^{-a(\tau-t^g)}, X^{gap}(\tau)) - \delta_g\right]d\tau$$

□

Proof of Proposition 5.

Proof. First we show that both g and x cannot be interior during the same time interval. For $U(G,X) = u(G+\eta X)$, we have $U_G = u'$ and $U_X = u'\eta$ If g is interior, (4) can be written $u' = (a+r)c_g + \delta_g$. Similarly, if x is interior, (5) can be written $u'\eta = (a+r)c_x + \delta_x - \dot{c}_x$. Combining these implies

$$\eta[(a+r)c_g + \delta_g] = (a+r)c_x(t) + \delta_x(t) - \dot{c}_x(t).$$

Since the left side of this equation is constant but the right side is decreasing, both g and x cannot be interior over an open interval, which implies $t^g \leq t^e$.

We now show that $t^g < t^e$. Suppose that $t^g = t^e$. Because g is interior, $\alpha = c_g$ on the interval $[0, t^g]$. In particular, $\alpha(t^g) = c_g$. However, using (A-3) from Lemma 2, we have

$$\alpha(t) = e^{(a+r)t} \int_t^\infty e^{-(a+r)\tau}[u'(G(\tau) + \eta X(\tau)) - \delta_g] d\tau$$

when we substitute in $U_G = u'$. Because $u'\eta = (a+r)c_x + \delta_x - \dot{c}_x$ after t^e, we have that u' is decreasing after t^e. This implies that

$$\begin{aligned}
\alpha(t^g) &= e^{(a+r)t^g} \int_{t^g}^\infty e^{-(a+r)\tau}[u'(G(\tau) + \eta X(\tau)) - \delta_g] d\tau \\
&< e^{(a+r)t^g} \int_{t^g}^\infty e^{-(a+r)\tau}[u'(G(t^g)) - \delta_g] d\tau \\
&= e^{(a+r)t^g}[u'(G(t^g)) - \delta_g] \int_{t^g}^\infty e^{-(a+r)\tau} d\tau \\
&= e^{(a+r)t^g}[(a+r)c_g] e^{-(a+r)t^g}/(a+r) = c_g
\end{aligned}$$

which is a contradiction.

□

D Temporary cessation of gasoline vehicle production

It may be optimal to stop producing gasoline vehicles and draw down the existing vehicle stock even if gasoline vehicles must eventually be produced in the terminal steady state. To illustrate the possibilities, assume the condition $U_G(0, X^*) > (a+r)c_g + \delta_g$ from Proposition 1 holds so that gasoline vehicle production is positive in the terminal steady state. It may be optimal to temporarily cease gasoline vehicle production if electric vehicles are good substitutes for gasoline vehicles for most uses, but are not good substitutes for other uses. For example, the benefit function

$$U = u(\min\{(n+1)G, X+G\})$$

has kinked indifference curves and implies that gasoline and electric vehicles are perfect substitutes if $G > X/n$ but that the marginal benefit of an electric vehicle is zero if $G < X/n$. In this example, if electric vehicles become cheaper than gasoline vehicles, the planner stops producing gasoline vehicles and begins to produce electric vehicles because the vehicles are perfect substitutes when $G > X/n = 0$. Over time, the stock of gasoline vehicles depreciates and the stock of electric vehicles grows. When $G = X/n$, the planner optimally restarts production of gasoline vehicles to hold production at the kink of the indifference curve where $G = X/n$. Thus gasoline vehicle production may be ceased temporarily if the substitutability of the vehicles depends on the stock of vehicles.

Temporarily ceasing gasoline vehicle production can also be optimal if the full marginal costs of electric vehicles are falling dramatically enough. To illustrate, suppose that both gasoline and electric vehicles are being produced so that both (4) and (5) hold. Taking the time derivative of these equations gives

$$U_{GX}\dot{X} + U_{GG}\dot{G} = 0$$

and

$$U_{XX}\dot{X} + U_{GX}\dot{G} = (a+r)\dot{c}_x + \dot{\delta}_x - \ddot{c}_x.$$

Solving this system for $\dot{G}$ gives

$$\dot{G} = \frac{(a+r)\dot{c}_x + \dot{\delta}_x - \ddot{c}_x}{-\frac{U_{XX}U_{GG}}{U_{GX}} + U_{GX}} \tag{A-9}$$

which is negative implying that the gasoline stock is decreasing. However, the decrease of the stock of gasoline vehicles is limited by the retirement rate. If $\dot{G}$ in (A-9) is more negative than $-aG$, then implied gasoline vehicle production would be negative. In this case, it is optimal to cease production of gasoline vehicles temporarily even though they are eventually produced in the steady state. Because the numerator on the right-hand-side of (A-9) is the time derivative of the full marginal cost of electric vehicles, a temporary cessation of gasoline vehicle production arises if the full marginal cost of electric vehicles is falling sufficiently fast relative to the depreciation rate of gasoline vehicles.

E Extensions

This appendix analyzes learning by doing and investment in charging infrastructure. To account for charging infrastructure, the benefit function becomes $U(G, X, W)$ where W is the stock of charging infrastructure and $U_W > 0$ and $U_{XW} > 0$. As W increases, electric vehicles become better substitutes for gasoline vehicles. Charging infrastructure grows based on investment, w, which costs c_w per unit and increases the stock according to the state equation $\dot{W} = w$ (which assumes investments do not depreciate). To account for learning by doing, assume the cost for producing an electric vehicle depends on the cumulative number of electric vehicles produced, Z, which follows the state equation $\dot{Z} = x$. The cost per electric vehicle then becomes

$$c_x = f(Z),$$

where $f'(Z) \leq 0$ and $f(\infty) = \hat{c}_x$. For notational convenience, assume f is not a function of time.

The finite horizon planner's problem with terminal time T is

$$\begin{aligned}
\max_{g,x,w} \quad & c_g e^{-rT} G(T) + f(Z(T)) e^{-rT} X(T) + \int_0^T e^{-rt} \left(U(G,X,W) - c_g g - f(Z)x - c_w w - \delta_g G - \delta_x X \right) dt \\
\text{s.t.} \quad \dot{G} &= -aG + g \ ; \ G(0) = G^{ss} \\
\dot{X} &= -aX + x \ ; \ X(0) = 0 \\
\dot{W} &= w \ ; \ W(0) = 0 \\
\dot{Z} &= x \ ; \ Z(0) = 0 \\
g &\geq 0 \\
x &\geq 0 \\
w &\geq 0
\end{aligned}$$

Let $\tilde{\alpha}$, $\tilde{\beta}$, and $\tilde{\phi}$, and $\tilde{\lambda}$, be the adjoint variables corresponding to the system equations for G, X, W and Z. The Hamiltonian is

$$H = \tilde{\alpha}(-aG + g) + \tilde{\beta}(-aX + x) + \tilde{\phi} w + \tilde{\lambda} x + e^{-rt} \left(U(G,X,W) - c_g g - f(Z)x - c_w w - \delta_g G - \delta_x X \right).$$

If T is long enough (and/or $Z(T)$ is big enough) so that $f(Z(T)) = \hat{c}_x$ and $f'(Z(T)) = 0$, using the change of variables $\alpha = e^{rt}\tilde{\alpha}, \beta = e^{rt}\tilde{\beta}, \phi = e^{rt}\tilde{\phi}$, and $\lambda = e^{rt}\tilde{\lambda}$ (i.e. current values instead of present values) the adjoint equations become

$$\dot{\alpha} = (a + r)\alpha - U_G + \delta_g \ ; \alpha(T) = c_g$$

$$\dot{\beta} = (a + r)\beta - U_X + \delta_x \ ; \beta(T) = \hat{c}_x$$

$$\dot{\phi} = r\phi - U_W \ ; \ \phi(T) = 0.$$

$$\dot{\lambda} = r\lambda + f'(Z)x \ ; \lambda(T) = 0$$

and the Kuhn-Tucker necessary conditions for g, x, and w become

$$\begin{array}{llll}
g \geq 0 & \alpha - c_g \leq 0 & (\alpha - c_g)g = 0 & \text{(necessary condition for } g) \\
x \geq 0 & \lambda + \beta - f(Z) \leq 0 & (\lambda + \beta - f(Z))x = 0 & \text{(necessary condition for } x) \\
w \geq 0 & \phi - c_w \leq 0 & (\phi - c_w)w = 0 & \text{(necessary condition for } w)
\end{array} \qquad \text{(A-10)}$$

For interior investment in charging infrastructure, $w > 0$ implies that $\phi = c_w$. Taking the time derivatives shows that $\dot{\phi} = 0$. The adjoint equation then implies that

$$U_W = rc_w \tag{A-11}$$

whenever charging infrastructure is positive.

For positive electric vehicle production, Eq. 5 in the main paper must be modified to account for the benefit of electric vehicle production on costs through learning. If $x > 0$, then $\lambda + \beta = f(Z)$ and taking the time derivative implies that $\dot{\lambda} + \dot{\beta} = f'(Z)x$. Substituting in the adjoint equations implies that

$$U_X = (a + r)\beta + \delta_x + r\lambda. \tag{A-12}$$

Unfortunately, both λ and β cannot be eliminated from this equation because there is only one choice variable. Thus the analog to Eq. 5 cannot be expressed independently of the shadow values.

Charging Infrastructure

This section focuses on charging infrastructure and ignores learning by doing. Assume that $U_W(G, 0, W) = 0$, which implies that the marginal benefit of charging stations is zero when there are no electric vehicles. Let t^w be the time at which the planner begins production of charging stations. We now prove a proposition that relates t^w and t^e.

Proposition 6. *If t^w is the time at which investment in charging infrastructure begins, then $t^w > t^e$.*

Proof. Suppose $t^w \leq t^e$. By assumption at t^w, w is interior which implies that $U_W(G, X, W) = rc_w$. But because $t^w \leq t^e$, we have $X(t^w) = 0$, so $rc_w = U_W(G(t^w), X(t^w), W(t^w)) = U_W(G(t^w), 0, W(t^w)) = 0$ which is a contradiction because $r > 0$. □

The proposition implies that electric vehicle production optimally begins before investment in charging infrastructure occurs. Because there is no benefit from charging infrastructure in the absence of electric vehicles, the planner waits until there are sufficient electric vehicles to warrant infrastructure investment. This result relies on the assumption of constant costs of infrastructure investment. If costs are convex, the planner may optimally invest in charging infrastructure earlier. In fact, with a capacity constraint on infrastructure investment, the planner may begin infrastructure investment strictly before any electric cars are built. In this case, investment would occur at its maximum rate until after electric car production begins.

Learning By Doing

This section focuses on learning by doing and ignores charging infrastructure. We begin by showing a few facts about the adjoint variables.

Lemma 3. *1. For all $t \in [0, T]$ we have $\lambda \geq 0$ and $\phi \geq 0$.*

2. If x is interior, then $\dot{\beta} = -r\lambda$.

3. If x is zero for $t \in [0, t^s)$ and interior for $t \in [t^s, T]$ for some t^s, then $\beta(t^s) < f(0)$ and $\beta \geq c_g$ for $t \in [t^s, T]$.

Proof. Suppose that at some point in time $\lambda < 0$. Because $f'(Z)x \leq 0$, it follows from the adjoint equation for λ that $\dot{\lambda} < 0$. Thus λ must continue to fall for the rest of the time period. But this is a contradiction with $\lambda(T) = 0$. The proof for ϕ is similar.

Next suppose that x is interior. Take the time derivative of (A-10). This gives

$$\dot{\lambda} + \dot{\beta} = f'(Z)x.$$

Using the adjoint equation for λ this implies

$$r\lambda + f'(Z)x + \dot{\beta} = f'(Z)x.$$

Simplifying gives the desired result that

$$\dot{\beta} = -r\lambda.$$

The fact that $\beta(t^s) < f(0)$ follows directly from (A-10) and the fact that $\lambda \geq 0$. To prove that $\beta \geq c_g$, we combine

$$\dot{\beta} = -r\lambda \leq 0.$$

with $\beta(T) = c_g$. □

Now assume the benefit function is $u(G + \eta X)$ so that gasoline and electric vehicles are perfect substitutes. The main text showed that such a benefit function leads to the gap solution. The next proposition shows this result is robust to the having the cost of electric vehicles be determined by learning by doing.

Proposition 7. *Consider the model with learning by doing. Suppose that benefit function is given by $u(G + \eta X)$. Then the solution to the planner's problem has $t^g < t^e$.*

Proof. First we show that both g and x cannot be interior during the same time interval. Suppose both g and x are interior during some time interval. Because g is interior, (4) implies

$$u' = (a + r)c_g + \delta_g.$$

Because x is interior, (A-12) implies

$$u'\eta = r(\lambda + \beta) + a\beta + \delta_x. \tag{A-13}$$

Substituting the value for u' from above and using (A-10) gives

$$rf(Z) + a\beta + \delta_x = ((a + r)c_g + \delta_g)\eta.$$

Taking the time derivative gives

$$rf'(Z)x + a\dot{\beta} + \dot{\delta}_x = 0 \tag{A-14}$$

From Lemma 3 we know that

$$\dot{\beta} = -r\lambda.$$

So we have

$$rf'(Z)x + \dot{\delta}_x = ar\lambda.$$

The first expression on the left-hand-side is non-positive and the second expression is negative. This implies that λ is negative, which contradicts Lemma 3.

So far we have shown that $t^g \le t^e$. So we must rule out the case that $t^g = t^e$. Suppose that t^g does indeed equal t^e. In steady state with g interior, we have $\alpha = c_g$, thus $\dot{\alpha} = 0$, and hence $u' - (a + r)c_g - \delta_g = 0$. These equations hold at $t = t^g$. Because $t^g = t^e$, we are also producing electric vehicles with interior x. From (A-13) and (A-10) we have

$$r(f(Z)) + a\beta + \delta_x = u'\eta. \tag{A-15}$$

Taking the time derivative gives

$$\eta\dot{u'} = rf'(Z)x + a\dot{\beta} + \dot{\delta}_x.$$

Every term on the right hand side is negative, hence $\dot{u'}$ is negative. Thus marginal benefit is decreasing over time.

Now consider some point in time $\tilde{t} = t^g + \varepsilon$. Because $\dot{\alpha} = 0$ at t^g, we have $\alpha = c_g$ at $\tilde{t}$. So at $\tilde{t}$, the adjoint equation for α is

$$\dot{\alpha} = -(u' - (a + r)c_g - \delta_g).$$

Because marginal benefit is decreasing over time, u' is less at $\tilde{t}$ than it is at t^g. At t^g we have $u' - (a + r)c_g - \delta_g = 0$. So at $\tilde{t}$ we have $u' - (a + r)c_g - \delta_g < 0$. Hence at $\tilde{t}$ we have $\dot{\alpha} > 0$. So this implies α will become greater than c_g in the next time instant. But, from the necessary conditions, if $\alpha > c_g$ then it is optimal for g to be positive (equal to the maximum production level.) This contradicts the definition of t^g. □

F Calibration Details

Gasoline vehicles

To understand the implications of our assumption that usage costs for gasoline vehicles are constant over time, consider evidence about various components of these usage costs. The externality component is equal to the product of damage valuation per unit of emissions and the emissions rates per mile driven. Damage valuations (in particular, the social cost of carbon) have been increasing over time, but emission rates have been declining. Historical emission rates from gasoline vehicles for 5 pollutants (VOC, CO_2, SO_2, $PM_{2.5}$, and NO_X) are given Table A. Many of these values simply reflect the emissions regulations in place at various points in time.

Although the pattern of declining emissions over time can be seen in the data in Table A, converting emissions to a single measure of damages illustrates this more clearly. Following the methodology of Holland et al (2016) and Holland et al (2018), we combine the emissions in grams per mile with the estimates of damage valuations in dollars per gram by county using the AP3 integrated assessment model which assumes a $9 million value of statistical life (VSL), the EPA social cost of carbon (SCC) of $45 per ton, and VMT by county. We then conduct an experiment in which we assume the 2015 fleet of vehicles has the polluting characteristics of, say, 1975 vintage passenger vehicles. Repeating this for each year in our historical time series gives the results shown in Figure A. In this figure, the damage valuations of pollutants are kept constant. The only thing that is changing is the emissions rates of the vehicles. The major improvements in emission reductions occur in the late 1970's and the 1990's, although there continues to be improvement over the recent decade, with damages decreasing approximately two percent per year.

Next consider the operating cost component. These costs depend on vehicle miles travelled (VMT), the miles per gallon of the vehicle, and the price of gasoline, which have stayed fairly constant over the last decade. Putting all of these elements together, our assumption that usage costs are constant is implicitly assuming that reductions in emissions rates over time just balance out increasing damage valuations for carbon and other pollutants. In particular, each new vintage of automobile must improve enough such that the usage costs from

Table A: Historical Emissions from Gasoline Vehicles (g/mile)

Model Year	CO_2	SO_2	$PM_{2.5}$	VOC	NO_X
1975	658	0.20881	0.0173	1.557	3.1
1976	596	0.18919	0.0173	1.557	3.1
1977	570	0.18071	0.0173	1.557	2
1978	526	0.16680	0.0173	1.557	2
1979	517	0.16390	0.0173	1.557	2
1980	444	0.14095	0.0173	1.557	2
1981	415	0.13173	0.0173	0.467	1
1982	400	0.12698	0.0173	0.467	1
1983	402	0.12756	0.0173	0.467	1
1984	397	0.12585	0.0173	0.467	1
1985	386	0.12257	0.0173	0.467	1
1986	375	0.11895	0.0173	0.467	1
1987	373	0.11845	0.0173	0.467	1
1988	369	0.11697	0.0173	0.467	1
1989	375	0.11895	0.0173	0.467	1
1990	381	0.12099	0.0173	0.467	1
1991	380	0.12047	0.0173	0.467	1
1992	385	0.12203	0.0173	0.467	1
1993	378	0.11996	0.0173	0.467	1
1994	381	0.12099	0.0173	0.307	0.6
1995	380	0.08192	0.0173	0.307	0.6
1996	381	0.08227	0.0173	0.307	0.6
1997	380	0.08192	0.0173	0.307	0.6
1998	380	0.08192	0.0173	0.307	0.6
1999	386	0.08334	0.0173	0.307	0.3
2000	388	0.04924	0.0173	0.307	0.3
2001	386	0.04903	0.0173	0.307	0.3
2002	385	0.04881	0.0173	0.307	0.3
2003	383	0.04860	0.0173	0.307	0.3
2004	385	0.02929	0.0173	0.132	0.07
2005	378	0.02159	0.0173	0.132	0.07
2006	381	0.00726	0.0173	0.132	0.07
2007	369	0.00702	0.0173	0.132	0.07
2008	366	0.00696	0.0173	0.132	0.07
2009	350	0.00666	0.0173	0.132	0.07
2010	344	0.00656	0.0173	0.132	0.07
2011	347	0.00661	0.0173	0.132	0.07
2012	328	0.00624	0.0173	0.132	0.07
2013	319	0.00606	0.0173	0.132	0.07
2014	319	0.00606	0.0173	0.132	0.07
2015	313	0.00596	0.0173	0.132	0.07

Notes: For 1975-2003, the NO_X standard comes from data in Mondt (2000). After 2003 the NO_X standard is average for Tier 2 bins phased in from 2004 to 2009. VOC emissions include tailpipe and evaporation. For 1975-2003, the tailpipe VOC emissions come from Lee et al (2011) and after 2003 tailpipe VOC emissions come from Tier 2 Bin 5. Evaporation VOC is fixed at the value specified GREET (2013). $PM_{2.5}$ includes tailpipe emissions (Tier 2 bin 5 standard) and tire and break wear from GREET 2013. Emissions of CO_2 are derived from fleet average MPG figures (EPA 2015, Table 9.1). SO_2 emissions are calculated from fleet average MPG figures and the sulphur content in gasoline (GREET 2013 and EPA (1999)).

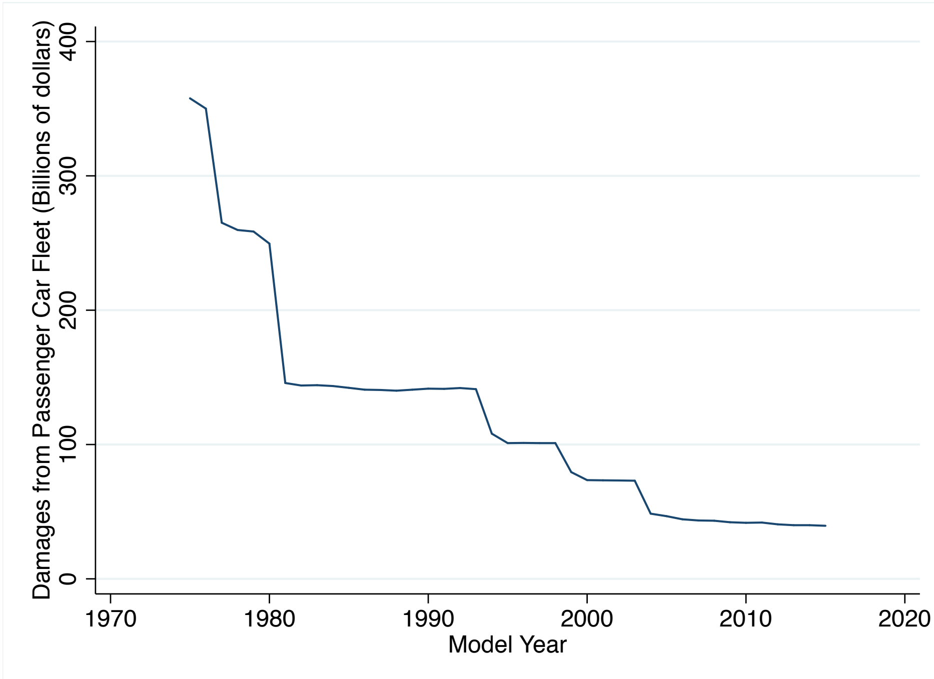


Figure A: Damages from Emissions of Gasoline Vehicles over Time

the entire stock of vehicles stays constant. This may be overly optimistic about the rate of improvements in gasoline technology.

To calibrate the externality component of the our usage costs, we use the emission rates the most recent vintage (2015) gasoline vehicle. The above procedure gives an externality component of usage costs of 2.3 cents per mile or $345 per vehicle per year assuming 15,000 miles per year. To calibrate the operating cost component of the usage costs, we use the American Automobile Association (2017) estimate of 18.18 cents per mile for the average gasoline vehicle in 2017 which corresponds to $2726 per year.[2]

For the production cost of gasoline vehicles, c_g, Kelley Blue Book (2017) reports the average transaction price for light duty vehicles of approximately $35000, which we adopt as our baseline value. This average is across all vehicle segments (e.g., including SUVs and electric vehicles) so is probably a high estimate for the production cost of passenger vehicles. To calibrate the stock of gasoline vehicles and their retirement rate, note that the 2015

[2]This is based on a gasoline price of $2.33 per gallon and includes costs for maintenance, repair, and tires of 7.91 cents per mile. We do not include costs for insurance, license, registration, or taxes which are quite similar across electric and gasoline vehicles. Depreciation and finance charges are modeled explicitly in the production cost of the vehicle.

stock of light duty vehicles is 190 million (Bureau of Transportation Statistics 2017) and approximately 58 percent of all light duty production from 1976 to 2016 is passenger cars (Bureau of Economic Analysis 2017). Assuming that passenger cars and light trucks retire at the same rate implies that the stock of passenger cars is 110 million. In steady state the retirement rate is the annual production divided by the stock. Over the period from 2012 to 2016, the average production of passenger cars is 7.4 million (Bureau of Economic Analysis 2017) which implies $a = 7.4/110 = 0.067$.

Electric vehicles

As with gasoline vehicles, usage costs for electric vehicles are comprised of externality cost and operating cost. The externality cost depends on VMT, electricity use per mile, and the marginal damage from the electricity usage. Estimates from Holland et al (2018) for the East show that damages per year are declining at approximately 5 percent per year and are equal to $332 dollars per year in 2017.[3] Converting this to the base year gives the externality cost function $605e^{(-0.05t)}$, where t is relative to 2005. The estimates in Holland et al (2018) do account for increasing damage valuations over time, but as with gasoline vehicles, our assumptions are likely optimistic about the rate of improvements from electric technology. Holland et al (2018) point out that the time period in their analysis is characterized by unusually rapid decreases in emissions. Our externality cost function assumes this rate of decline continues such that the externality cost approaches zero in the limit. Using a methodology similar to that for gasoline vehicles, the American Automobile Association (2017) estimate the operating cost of electric vehicle in 2017 to be 10.23 cents per mile or $1535 per year.[4]

For the production cost of electric vehicles, we assume that most of the changes in cost is due to decreased cost for the batteries. Data on prices and production of Lithium ion batteries, expressed in 2015 dollars, comes from Kittner, Lill, and Kammen (2017) and is shown in Table B. The general procedure for specifying c_x is to determine an initial cost premium in conjunction with an exponential decay function that is a function of time and

[3]Marginal damages are 6.5 cents per kWh and VMT-weighted electricity use is 0.341kWh per mile.

[4]Again this includes maintenance costs of 6.55 cents per mile, but we do not include costs for insurance and fees.

cumulative production. We assume that electric vehicles have a 60 KWh battery and convert the units of cumulative production into millions of vehicles (divide MWh by 60,0000) to be consistent with the rest of the parameters. We then estimate the following model for battery prices

$$\ln(\text{Price}) = constant + \alpha\text{Year} + \beta \ln(\text{Cumulative Production}) + \varepsilon.$$

Using OLS, we obtain $\alpha = -0.06$ (Std. Err. 0.01) and $\beta = -0.16$ (Std. Err. 0.02). For the simulation, we start in year 2005. Under the assumption that costs are a function of time alone we get

$$c_x = c_g + 1.04 * 60 * 351.95e^{-0.06t},$$

where 1.04 converts from 2015 dollars to 2017 dollars, 60 is the size of the battery, 351.95 is the cost of batteries in 2005, and 0.06 is the estimate of α. Adding learning by doing gives

$$c_x = c_g + 1.04 * 60 * 351.95e^{-0.06t-0.16\ln(Z+1)},$$

where Z is the cumulative production of electric vehicles. In this formulation, learning by doing combines with exogenous decreases in costs over time, and, when $Z = 0$, the cost corresponds to the baseline specification in which costs are a function of time alone.

Our calibration shows that the initial annual usage costs in 2005 of electric vehicles, \$2167, is less than the usage cost for the gasoline vehicle, \$3022. But initial full marginal costs for electric vehicles, \$9000, are higher than full marginal costs of gasoline vehicles, \$7000, due to the higher production costs of electric vehicles. In the limit, full marginal costs of electric vehicles fall to a level about \$1000 lower than gasoline vehicles.

Benefit Function

We use observed data on prices and quantities in 2018 to calibrate the benefit function parameters A, η, and γ. The necessary conditions (4) and (5) are two suitable equations if we modify the costs to reflect the actual costs faced by consumers.[5] For the third equation, we

[5] In particular, the calibration ignores the externality costs and reduces the electric vehicle cost by \$7500 to reflect existing subsidies.

Table B: Price and Cumulative Production of Lithium Ion Batteries

Year	Price (2015 Dollars per KWh)	Cumulative Production (MWh)
1991	5394.66	0.13
1992	4392.33	1.68
1993	3444.54	14.55
1994	2718.82	50.08
1995	2566.13	121.13
1996	1888.28	547.42
1997	1329.07	1257.9
1998	872.46	2288.09
1999	711.34	3815.63
2000	619.38	5982.59
2001	508.85	8504.79
2002	487.47	12092.71
2003	437.97	17350.26
2004	401.51	24526.11
2005	351.95	33371.58
2006	317.43	44916.87
2007	320.07	58806.74
2008	319.25	75616.08
2009	298.29	94954.08
2010	260.87	119308.1
2011	231.81	149029.1
2012	185.82	183816.1
2013	183.14	226555.1
2014	170.2	276384.1
2015	150	337871.1

first determine a formula for the cross-price elasticity $\epsilon_{Gp_X} = p_x/G \cdot dG/dp_x$. Then, using data from Xing et al (2019), we determine a numerical value of 0.01 for the cross price elasticity, which we adopt as our baseline value (see below for the details of these steps). Setting our cross-price elasticity formula equal to 0.01 gives a third equation, which allows us to solve for the three benefit function parameters. Note that our functional form and calibration imply an own price elasticity of approximately -1, which is reasonable but smaller than many estimates. We could alternatively calibrate based on own-price elasticity estimates. However, due to the importance of the substitutability of electric and gasoline vehicles in our theory, we prefer to calibrate using the cross-price elasticity.[6] This calibration yields the baseline values in the first column of Table C. The other columns show parameter values for different assumed values of the cross-price elasticity.

To determine the formula for the cross-price elasticity, we start with the benefit function:

$$U(G, X) = A \ln(G + \eta X + \gamma \eta G X). \qquad \text{(A-16)}$$

[6]The more flexible functional form allows us to match an own- and cross-price elasticity but does not change the results substantially.

Table C: Benefit parameters as a function of cross-price elasticity

Parameter	$\epsilon_{Gp_X} = 0.01$	$\epsilon_{Gp_X} = 2$	$\epsilon_{Gp_X} = 5.5$	$\epsilon_{Gp_X} = 8$
A	750,376	755,413	756,277	756,449
η	0.00974529	0.749591	0.875532	0.900464
γ	0.892332	0.00254949	0.000863579	0.000585756

Setting the marginal rate of substitution equal to the price ratio implies:

$$p_X(1+\gamma\eta X) = p_G(\eta + \gamma\eta G) \tag{A-17}$$

where p_X and p_G are the prices of electric and gasoline vehicles. Setting the marginal benefit of a gasoline vehicle equal to its price implies that

$$A(1+\gamma\eta X) = p_G(G + \eta X + \gamma\eta GX).$$

Using [A-17] to eliminate X implies that the demand for G is implicitly defined by

$$A = p_G G + \frac{p_G}{\gamma} - \frac{p_X}{(1+\gamma G)\gamma\eta}.$$

Taking the derivative of this equation, we can derive the cross-price elasticity formula:

$$\epsilon_{Gp_X} = \frac{p_X}{G}\frac{dG}{dp_X} = \frac{p_X}{G}\frac{1+\gamma G}{\gamma[\eta(1+\gamma G)^2 p_G + p_X]}.$$

Xing et al (2019) analyze the state of the market for electric vehicles as of 2014. We use several pieces of information from this study to determine the numerical value for the cross-price elasticity. Table 8 in Xing et al (2019) shows the effect of removing the $7500 subsidy for electric vehicles is a 0.23% increase in the sales of gasoline vehicles. Table D.2 in Xing et al (2019) shows that the average electric vehicle pre-subsidy price in their data is $32,580, so the average post-subsidy price is $25080. Removing the subsidy thus increases the price of electric cars to consumers from $25,080 to $32,580. Hence the cross price elasticity is

$$\frac{0.23}{\frac{7500}{25080}} = 0.0077,$$

which we round to 0.01.

G Additional Second Best Policies

In this section we analyze several additional second best policies. For purchase subsidies on electric vehicles, consider the price path

$$\tilde{c}_x = (c_g - \psi_1) + (21961 - \psi_2)e^{-(0.06-\psi_3)t}.$$

In the main text, we set ψ_2 and ψ_3 equal to zero and selected the value of ψ_1 to minimize deadweight loss, which gave us the results for the EV Subsidy policy. By setting ψ_1 and ψ_3 equal to zero an selecting the value of ψ_2 to minimize deadweight loss, we get the results in the EV Initial Price Subsidy rows in Table D. Similarly, the results in the EV Decay Subsidy rows reflect the optimization with respect to ψ_3, and the results in the EV Two Parm Subsidy rows reflect the joint optimization over ψ_1 and ψ_2. As would be expected, the policy in which two parameters are optimized has the lowest deadweight loss. There is no consistent ranking between the single parameter policies.

Next we consider a GV Flexible Quota policy that is a generalization of the GV Quota policy in the main text. Consider the state equation

$$\dot{H} = g - \kappa.$$

In the main text, we assumed that $\kappa = 0$ and placed a constraint $\mathcal{G}$ on the state variable H. Thus H was interpreted as cumulative production of gasoline vehicles. The GV Flexible Quota policy allows for a constraint on instantaneous production (when $\mathcal{G} = 0$) as well as a hybrid policy (when both $\mathcal{G}$ and κ are positive). The results for this policy are shown in the GV Flexible Quota rows. In panels C and D, the GV Flexible Quota policy essentially has no impact. The optimal value of κ is zero or close to zero, and so the results are essentially the same as with the GV Quota policy. In panel A, the optimal policy is a constraint on instantaneous production. This policy dramatically decreases the deadweight loss because it is acting similar to a first best Pigovian tax on the externality from gasoline vehicles. In panel B the optimal policy has positive values for both $\mathcal{G}$ and κ.

The final point to make about Table D is about the GV Quota rows in Panels A and B. Even though the first best solution allows positive production of gasoline cars in the long run steady state, a quota can lower deadweight loss for a given terminal time.

Table D: Second Best Policy Results: Additional Policies

Policy	Optimal Parameter	Deadweight Loss ($ billions)	Transition Time t^e (Year)	t^g (Year)	Terminal State G^T	X^T
	Panel A: Low cross-price elasticity: $\epsilon_{Gp_X} = 0.01$					
First Best	n.a.	0	2031.4	n.a.	104.5	17.3
BAU	n.a.	18.5	2028.4	n.a.	109.8	17.7
EV Subsidy	ψ_1= -762	18.0	2030.0	n.a.	109.8	15.7
EV Initial Price Subsidy	ψ_2= -4604	17.9	2031.5	n.a.	109.8	17.4
EV Decay Subsidy	ψ_3= 0.007	18.0	2030.6	n.a.	109.8	16.9
EV Two Parm Subsidy	ψ_1= -81 ψ_2= -4190	17.9	2031.4	n.a.	109.8	17.2
GV Ban	t^g = n.a. (no ban)	18.5	2028.4	n.a.	109.8	17.7
GV Quota	$\mathcal{G}$ = 469*	15.8	2028.4	2069.9	90.9	17.9
GV Flexible Quota	$\mathcal{G}$ = 0 κ= 7.0	0.6	2028.3	n.a.	104.5	17.8
	Panel B: Medium cross-price elasticity: $\epsilon_{Gp_X} = 2$					
First Best	n.a.	0	2027.8	n.a.	68.7	53.9
BAU	n.a.	20.9	2028.9	n.a.	81.0	42.9
EV Subsidy	ψ_1= 1090	18.3	2026.8	n.a.	76.3	50.2
EV Initial Price Subsidy	ψ_2= 3255	19.6	2026.3	n.a.	80.6	43.5
EV Decay Subsidy	ψ_3= -0.009	19.0	2026.6	n.a.	79.9	44.5
EV Two Parm Subsidy	ψ_1= 1668 ψ_2= -2984	18.1	2027.9	n.a.	74.2	53.6
GV Ban	t^g = n.a. (no ban)	20.9	2028.9	n.a.	81.0	42.9
GV Quota	$\mathcal{G}$ = 348*	15.9	2028.2	2064.4	42.7	81.1
GV Flexible Quota	$\mathcal{G}$ = 53 κ= 4.7	7.5	2025.0	n.a.	71.4	51.8
	Panel C: High cross-price elasticity: $\epsilon_{Gp_X} = 5.5$					
First Best	n.a.	0	2027.3	2036.9	5.6	125.7
BAU	n.a.	28.9	2029.1	n.a.	30.2	99.0
EV Subsidy	ψ_1= 1419	18.6	2026.4	n.a.	13.6	121.2
EV Initial Price Subsidy	ψ_2= 4263	23.4	2025.6	n.a.	28.8	100.7
EV Decay Subsidy	ψ_3= -0.012	21.3	2026.1	n.a.	26.6	103.7
EV Two Parm Subsidy	ψ_1= 1988 ψ_2= -2873	18.0	2027.4	n.a.	7.8	129.1
GV Ban	t^g = 2026.5	18.7	2028.7	2026.5	6.1	125.7
GV Quota	$\mathcal{G}$ = 161	8.7	2026.5	2026.4	5.1	126.8
GV Flexible Quota	$\mathcal{G}$ = 160 κ= 0.0	8.7	2026.5	n.a.	5.4	126.5
	Panel D: Very high cross-price elasticity: $\epsilon_{Gp_X} = 8$					
First Best	n.a.	0	2025.3	2025.0	4.5	127.1
BAU	n.a.	23.7	2028.9	2028.8	6.1	125.8
EV Subsidy	ψ_1= 1125	17.0	2025.7	2025.5	4.9	130.3
EV Initial Price Subsidy	ψ_2= 4181	16.4	2025.4	2025.3	4.9	127.5
EV Decay Subsidy	ψ_3= -0.010	16.6	2025.5	2025.4	4.9	128.0
EV Two Parm Subsidy	ψ_1= -330 ψ_2= 5315	16.4	2025.3	2025.3	4.8	126.7
GV Ban	t^g = 2023.8	18.1	2026.2	2023.8	5.0	127.0
GV Quota	$\mathcal{G}$ = 141	8.3	2024.2	2023.7	4.3	127.9
GV Flexible Quota	$\mathcal{G}$ = 141 κ= 0.0	8.3	2024.2	n.a.	4.3	127.9

Notes: For subsidy policies, the price path formula is $\tilde{c}_x = (c_g - \psi_1) + (21961 - \psi_2)e^{-(0.06-\psi_3)t}$, with default values $\psi_1 = 0$, $\psi_2 = 0$, $\psi_3 = 0$. The EV Two Parm Subsidy policy selects ψ_1 and ψ_2 to minimize deadweight loss and keeps ψ_3 fixed, the EV Subsidy policy optimizes ψ_1 and keeps ψ_2 and ψ_3 fixed; the EV Initial Price Subsidy policy optimizes ψ_2 and keeps ψ_1 and ψ_3 fixed; and so on. For GV Ban t^g indicates the year in which the ban is implemented. For GV Quota, $\mathcal{G}$ is the cumulative allowed production of gas vehicles. "*" indicates that the value is sensitive to the assumed 70 year finite horizon. G^T and X^T are the values at the end of the finite horizon.

H Sensitivity to the SCC and Interactions with Climate Policy

Table E shows how the second best results change when we vary the SCC. For $\epsilon_{Gp_X} = 5.5$, Panel A shows a very high SCC of \$200 and Panels B and C analyze modest decrements and increments to our baseline SCC.

We can also use our model to analyze the interaction between a (possibly imperfect) climate policy and the second best policies for electric vehicle adoption. In our model, the miles driven per year is constant for both vehicles. Accordingly, consider a tax on carbon emissions that is imposed when a new vehicle is purchased. This tax is equal to a fraction τ of the lifetime damages from CO_2 emissions. The CO_2 portion of the annual externality from gasoline vehicle usages is \$218 (out of a total of \$345). With a 15 year expected lifetime, the corresponding tax on the purchase of gasoline vehicle is $\theta * 218 * 15$. For electric vehicles, the initial portion of the annual externality from usage is \$297.6 (out of a total of 605). Assuming that this externality decreases at 5 percent per year, the tax on an electric vehicle purchased at time t_v is

$$\tau = \int_{t_v}^{t_v+15} 297.6 e^{-0.05t} dt.$$

Table F shows the results when we include these carbon taxes in addition to the electric vehicle policies. When $\tau = 1$, the carbon externalities are fully internalized in BAU, but there is still a small welfare loss from the local pollutants. In this case, the quota and ban policies do no offer any improvement relative to BAU. For other values of τ, the quota policy once again leads to the smallest deadweight loss.

I Changes in Substitutability

To account for endogenous changes in substitutability, we assume that the benefit function is given by

$$U(G,X,W) = A \ln(G + \eta(W)X + \gamma(W)\eta(W)GX)$$

Table E: Sensitivity Analysis for the SCC (ϵ_{Gp_X} = 5.5)

Policy	Optimal Parameter	Deadweight Loss ($ billions)	Transition Time t^e (Year)	t^g (Year)	Terminal State G^T	X^T
Panel A: ϵ_{Gp_X} = 5.5 Very High SCC						
First Best	n.a.	0	2021.6	2021.1	3.2	127.7
BAU	n.a.	256.2	2029.1	n.a.	30.2	99.0
EV Subsidy	ψ_1= 3445	155.1	2022.7	2022.6	4.1	138.0
EV Initial Price Subsidy	ψ_2= 9161	198.5	2020.1	n.a.	27.3	102.8
EV Decay Subsidy	ψ_3= -0.038	175.3	2021.5	n.a.	23.8	107.4
EV Two Parm Subsidy	ψ_1= 2706 ψ_2= 2835	153.0	2021.9	2025.5	3.9	136.1
GV Ban	t^g = 2018.3	157.8	2022.9	2018.3	3.9	128.2
GV Quota	$\mathcal{G}$ = 91	59.2	2018.7	2017.8	2.8	129.4
GV Flexible Quota	$\mathcal{G}$ = 91 κ= 0.0	59.2	2018.8	n.a.	2.8	129.4
Panel B: ϵ_{Gp_X} = 5.5 High SCC						
First Best	n.a.	0	2027.0	2029.3	5.2	126.1
BAU	n.a.	38.6	2029.1	n.a.	30.2	99.0
EV Subsidy	ψ_1= 1649	24.4	2025.9	n.a.	10.9	124.9
EV Initial Price Subsidy	ψ_2= 4794	31.0	2025.0	n.a.	28.7	101.0
EV Decay Subsidy	ψ_3= -0.014	28.1	2025.6	n.a.	26.2	104.2
EV Two Parm Subsidy	ψ_1= 2186 ψ_2= -2749	23.7	2027.0	2049.1	6.2	131.5
GV Ban	t^g = 2025.8	24.5	2028.2	2025.8	5.8	125.9
GV Quota	$\mathcal{G}$ = 154	11.1	2025.7	2025.6	4.8	127.1
GV Flexible Quota	$\mathcal{G}$ = 154 κ= 0.0	11.1	2025.7	n.a.	4.8	127.1
Panel C: ϵ_{Gp_X} = 5.5 Low SCC						
First Best	n.a.	0	2027.7	2055.2	6.6	124.6
BAU	n.a.	20.4	2029.1	n.a.	30.2	99.0
EV Subsidy	ψ_1= 1180	13.4	2026.8	n.a.	16.4	117.4
EV Initial Price Subsidy	ψ_2= 3629	16.7	2026.1	n.a.	29.0	100.5
EV Decay Subsidy	ψ_3= -0.010	15.3	2026.6	n.a.	27.1	103.1
EV Two Parm Subsidy	ψ_1= 1690 ψ_2= -2625	13.0	2027.8	n.a.	11.3	124.4
GV Ban	t^g = 2027.4	13.7	2029.3	2027.4	6.4	125.3
GV Quota	$\mathcal{G}$ = 168	6.6	2027.3	2027.3	5.5	126.4
GV Flexible Quota	$\mathcal{G}$ = 158 κ= 0.3	6.5	2027.0	n.a.	9.8	121.5

Notes: For subsidy policies, the price path formula is $\tilde{c}_x = (c_g - \psi_1) + (21961 - \psi_2)e^{-(0.06-\psi_3)t}$, with default values $\psi_1 = 0$, $\psi_2 = 0$, $\psi_3 = 0$. The EV Two Parm Subsidy policy selects ψ_1 and ψ_2 to minimize deadweight loss and keeps ψ_3 fixed, the EV Subsidy policy optimizes ψ_1 and keeps ψ_2 and ψ_3 fixed; the EV Initial Price Subsidy policy optimizes ψ_2 and keeps ψ_1 and ψ_3 fixed; and so on. For GV Ban, t^g indicates the year in which the ban is implemented. For GV Quota, $\mathcal{G}$ is the cumulative allowed production of gas vehicles. G^T and X^T are the values at the end of the finite horizon. Baseline SCC ($45.23), High SCC ($56.27) , and Low SCC ($34.20) correspond to the values used in Holland et al 2018. Very High SCC ($200) is similar to the value used in Moore and Diaz (2015).

Table F: Second Best Policy Results: Interaction with Climate Policy

Policy	Optimal Parameter	Deadweight Loss ($ billions)	Transition Time t^e (Year)	t^g (Year)	Terminal State G^T	X^T
Panel A: $\tau = 1$						
First Best	n.a.	0	2027.3	2036.9	5.6	125.7
BAU	n.a.	0.8	2026.5	2029.9	5.1	126.4
Subsidy: Constant	ψ_1= -383	0.2	2027.1	2039.0	5.6	124.8
Subsidy: Initial Price	ψ_2= -1647	0.2	2027.6	2030.9	5.4	125.8
Subsidy: Decay Rate	ψ_3= 0.003	0.2	2027.3	2034.8	5.5	125.5
Subsidy	ψ_1= -191 ψ_2= -899	0.2	2027.4	2034.3	5.5	125.3
Gas Production Ban	n.a	0.8	2026.5	2029.9	5.1	126.4
Gas Production Quota	n.a.	0.8	2026.5	2029.9	5.1	126.4
Gas Prod Quota Cons	n.a	0.8	2026.5	2029.9	5.1	126.4
Panel B: $\tau = 0.67$						
First Best	n.a.	0	2027.3	2036.9	5.6	125.7
BAU	n.a.	1.5	2027.3	n.a.	8.6	122.5
Subsidy: Constant	ψ_1= 217	1.2	2026.9	2057.5	6.4	125.6
Subsidy: Initial Price	ψ_2= 515	1.4	2026.9	n.a.	8.5	122.7
Subsidy: Decay Rate	ψ_3= -0.001	1.3	2026.9	n.a.	8.0	123.3
Subsidy	ψ_1= 435 ψ_2= -1173	1.1	2027.3	2042.8	5.9	126.7
Gas Production Ban	t^g = 2027.4	1.1	2027.9	2027.4	5.6	125.9
Gas Production Quota	$\mathcal{G}$ = 166	0.8	2027.1	2036.3	5.7	125.8
Gas Prod Quota Cons	$\mathcal{G}$ = 163 κ= 0.0	0.7	2027.0	n.a.	5.5	126.0
Panel C: $\tau = 0.34$						
First Best	n.a.	0	2027.3	2036.9	5.6	125.7
BAU	n.a.	10.4	2028.1	n.a.	19.1	111.0
Subsidy: Constant	ψ_1= 812	7.1	2026.6	n.a.	9.7	123.6
Subsidy: Initial Price	ψ_2= 2457	8.7	2026.2	n.a.	18.3	112.0
Subsidy: Decay Rate	ψ_3= -0.006	8.0	2025.9	n.a.	16.8	114.0
Subsidy	ψ_1= 1195 ψ_2= -1988	6.8	2027.4	2052.7	6.4	128.3
Gas Production Ban	t^g = 2026.9	7.1	2028.4	2026.9	5.9	125.7
Gas Production Quota	$\mathcal{G}$ = 162	3.6	2026.9	2026.9	5.3	126.5
Gas Prod Quota Cons	$\mathcal{G}$ = 161 κ= 0.0	3.6	2026.9	n.a.	5.5	126.2

Notes: All panels have $\epsilon_{Gp_X} = 5.5$. For subsidy policies, the price path formula is $\tilde{c}_x = (c_g - \psi_1) + (21961 - \psi_2)e^{-(0.06-\psi_3)t}$, with default values $\psi_1 = 0$, $\psi_2 = 0$, $\psi_3 = 0$. The EV Two Parm Subsidy policy selects ψ_1 and ψ_2 to minimize deadweight loss and keeps ψ_3 fixed, the EV Subsidy policy optimizes ψ_1 and keeps ψ_2 and ψ_3 fixed; the EV Initial Price Subsidy policy optimizes ψ_2 and keeps ψ_1 and ψ_3 fixed; and so on. For GV Ban t^g indicates the year in which the ban is implemented. For GV Quota, $\mathcal{G}$ is the cumulative allowed production of gas vehicles. of the finite horizon.

where W is the stock of infrastructure and the substitutability parameters $\eta(W)$ and $\gamma(W)$ are functions of W with limits $\eta(\infty) = 1$ and $\gamma(\infty) = 0$ such that electric and gasoline vehicles approach perfect substitutes as the investment in charging infrastructure increases. (For exogenous increases in substitutability, we simply replace W with ϕt.) We assume that γ exponentially decreases as W increases:

$$\gamma = \gamma_o e^{-W}.$$

As discussed in the main text, as γ changes, we adjust η such that the MRS at a particular point $(G^q, 0)$ stays equal to a constant value q. As illustrated in Figure B, this flattens the indifference curve through $(G^q, 0)$ such that, as W tends to infinity, the indifference curve approaches the tangent line at the point $(G^q, 0)$, i.e. the electric vehicle and the gasoline vehicle become perfect substitutes.

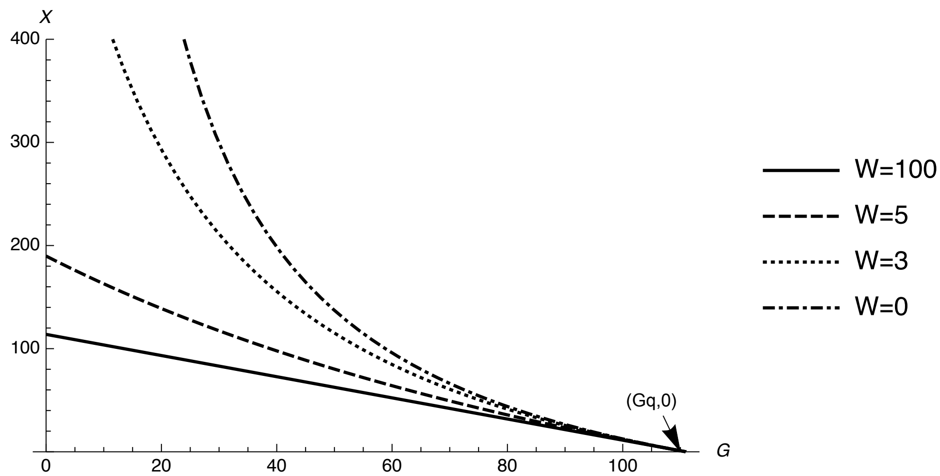


Figure B: Endogenous Substitutability: Indifference Curves as a function of W

Given our benefit function $U(G, X) = A \ln(G + \eta X + \gamma\eta GX)$ we have

$$MRS = \frac{1 + X\gamma\eta}{\eta + G\gamma\eta}. \tag{A-18}$$

Solving $MRS = q$ for η gives

$$\eta = \frac{1}{-X\gamma + q(1 + G\gamma)}.$$

Substituting in $(G^q, 0)$ gives

$$\eta = \frac{1}{q(1 + G^q\gamma)}.$$

This equation specifies how η changes as γ changes, and, in conjunction with (A-18), how η changes as W changes. It remains to define the values of G^q and q. Let $(G^q, 0)$ be on the same indifference curve as the initial point $(G^{2018}, X^{2018}) = (110, 1)$. Thus G^q satisfies

$$G^q + \eta_0(0) + \gamma_0\eta_0 G^q(0) = 110 + \eta_0(1) + \gamma_0\eta_0 110(1).$$

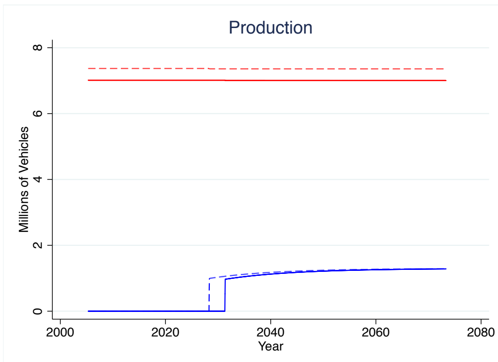
It follows that $G^q = 110.966309$. We find q by evaluating the MRS at $(G^q, 0)$ using η_0, and γ_0 corresponding to cross-price elasticity of 0.01. This gives $q = 1.02594397$.

Turning to simulation results, consider first exogenously increasing substitutability. The time paths of production for ϕ are given in Figure C. For low values of ϕ (Panels A and B) gasoline production is never halted. For intermediate values of ϕ there is a period of simultaneous production of gasoline and electric vehicles. For high values of ϕ, the first best features a gap solution.

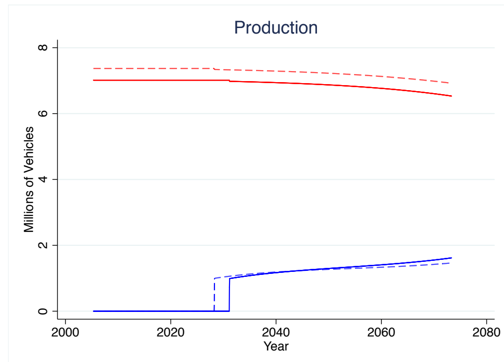
Figure D shows the time paths of vehicle production and stocks for very high cost and low cost charging infrastructure. In Panel A, charging infrastructure has very high costs, no investment occurs, and electric vehicles are simply adopted based on their low level of substitutability. In Panel B, charging infrastructure is low cost and hence is installed. Investment in charging infrastructure is very rapid and quickly makes electric vehicles nearly perfect substitutes for gasoline vehicles. Indeed, investment is so rapid that the gap solution occurs as evidenced by the decline in total vehicle stock before electric car production begins.

Table G shows the results of the additional policies for the increasing substitutability cases. In all three panels the optimal quota policy yields a constraint on instantaneous production. This does not mean that gasoline vehicles are produced over the whole time period. Rather the constraint only binds in the early years, and eventually gasoline production ceases.

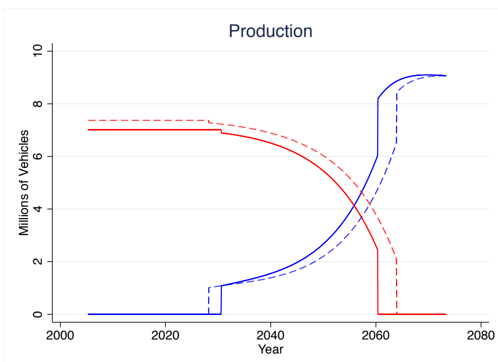
Figure C: Exogenously increasing substitutability



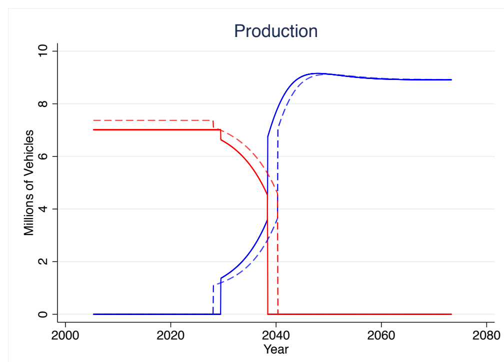
(a) Baseline ($\phi = 0$)



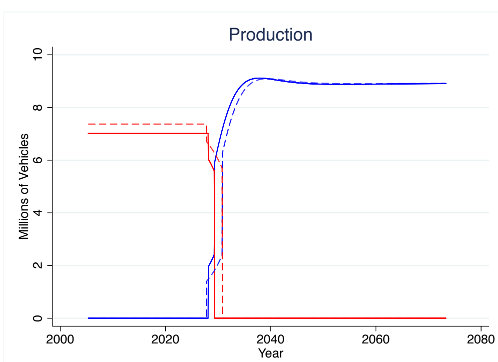
(b) $\phi = 0.05$



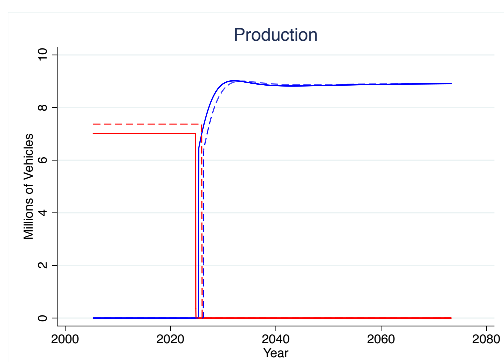
(c) $\phi = .10$



(d) $\phi = 0.15$



(e) $\phi = .20$

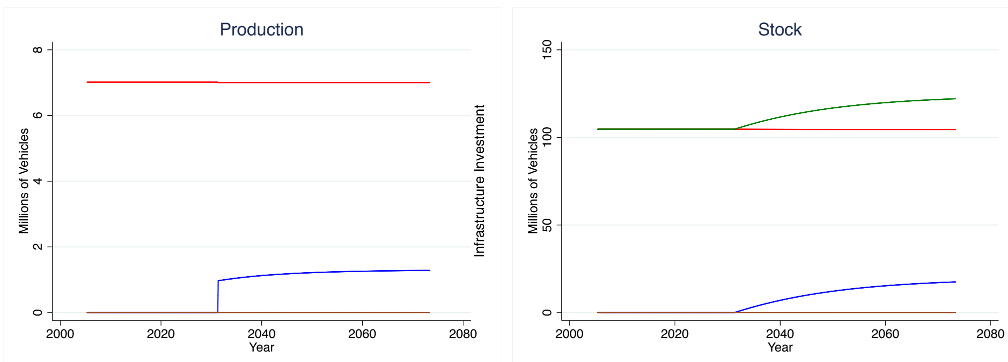


(f) $\phi = 0.25$

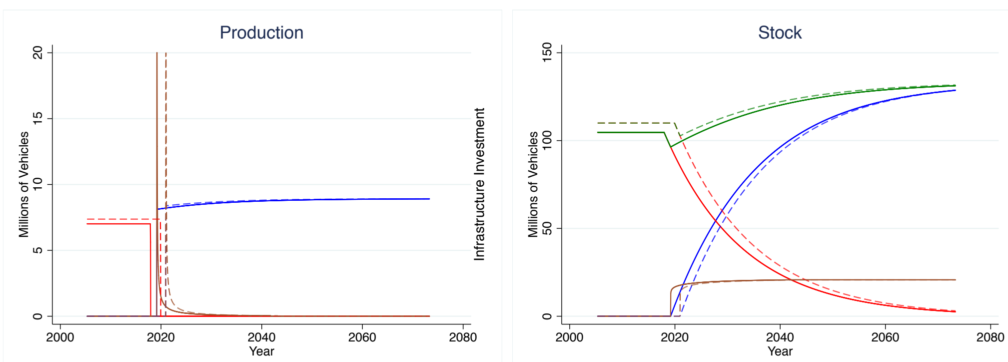
Notes: Red is gasoline vehicles, blue is electric vehicles. Solid is "First Best" and includes all costs. Dashed is "BAU" and ignores all externalities. Figure shows different values of ϕ where $\gamma = \gamma_0 e^{-\phi t}$, γ_0 corresponds the cross price elasticity of 0.01, and η is adjusted as γ changes in the same manner as in Figure D.

Figure D: Endogenously Increasing Substitutability

Panel A: Very High Cost Infrastructure



Panel B: Low Cost Infrastructure



Notes: Red is gasoline vehicles, blue is electric vehicles, green is total vehicles, and brown is charging infrastructure. Dashed is "BAU" and ignores all externalities.

Table G: Increasing Substitutability: Additional Policies

Policy	Optimal Parameter	Deadweight Loss ($ billions)	Transition Time t^e (Year)	t^g (Year)	Terminal State G^T	X^T
Panel A: Exogenous $\phi = 0.1$						
First Best	n.a.	0	2030.6	2060.4	36.1	91.1
BAU	n.a.	19.2	2028.3	2064.0	45.9	81.2
EV Subsidy	$\psi_1 = 357$	19.0	2027.6	2063.4	44.3	83.8
EV Initial Price Subsidy	$\psi_2 = -1143$	19.1	2029.1	2064.0	46.1	80.9
EV Decay Subsidy	$\psi_3 = 0.000$	19.2	2028.3	2064.0	45.9	81.2
EV Two Parm Subsidy	$\psi_1 = 1865$ $\psi_2 = -10581$	17.9	2031.4	2061.4	40.0	91.8
GV Ban	$t^g = 2057.6$	18.9	2028.3	2057.6	40.9	86.5
GV Quota	$\mathcal{G} = 341$	13.0	2028.1	2055.3	29.3	98.8
GV Flexible Quota	$\mathcal{G} = 0$ $\kappa = 6.9$	3.7	2027.7	2064.0	45.9	81.2
Panel B: Exogenous $\phi = 0.2$						
First Best	n.a.	0	2028.1	2029.3	5.9	125.0
BAU	n.a.	18.0	2027.8	2030.8	6.8	124.6
EV Subsidy	$\psi_1 = 734$	16.9	2026.5	2030.1	6.4	126.9
EV Initial Price Subsidy	$\psi_2 = 2828$	17.0	2025.7	2030.4	6.5	125.1
EV Decay Subsidy	$\psi_3 = -0.007$	16.8	2026.2	2030.2	6.4	125.5
EV Two Parm Subsidy	$\psi_1 = 670$ $\psi_2 = 284$	16.9	2026.4	2030.1	6.4	126.8
GV Ban	$t^g = 2028.2$	17.3	2029.3	2028.2	6.5	124.9
GV Quota	$\mathcal{G} = 167$	7.9	2026.6	2027.9	5.5	125.9
GV Flexible Quota	$\mathcal{G} = 0$ $\kappa = 7.0$	5.0	2025.8	2031.1	6.8	124.6
Panel C: Endogenous (infrastructure)						
First Best	n.a.	0	2019.2	2017.9	2.8	128.2
BAU	n.a.	18.7	2021.0	2019.9	3.4	128.1
EV Subsidy	$\psi_1 = 766$	15.8	2019.6	2018.5	3.0	130.5
EV Initial Price Subsidy	$\psi_2 = 2092$	15.2	2019.3	2018.3	3.0	128.6
EV Decay Subsidy	$\psi_3 = -0.006$	15.5	2019.5	2018.4	3.0	129.0
EV Two Parm Subsidy	$\psi_1 = -558$ $\psi_2 = 3414$	15.1	2019.2	2018.2	3.0	127.2
GV Ban	$t^g = 2017.1$	16.2	2019.9	2017.1	3.1	128.4
GV Quota	$\mathcal{G} = 91$	7.8	2018.3	2016.9	2.7	128.8
GV Flexible Quota	$\mathcal{G} = 0$ $\kappa = 6.8$	7.1	2020.5	2020.4	3.2	128.2

Notes: For subsidy policies, the price path formula is $\tilde{c}_x = (c_g - \psi_1) + (21961 - \psi_2)e^{-(0.06-\psi_3)t}$, with default values $\psi_1 = 0$, $\psi_2 = 0$, $\psi_3 = 0$. The EV Two Parm Subsidy policy selects ψ_1 and ψ_2 to minimize deadweight loss and keeps ψ_3 fixed, the EV Subsidy policy optimizes ψ_1 and keeps ψ_2 and ψ_3 fixed; the EV Initial Price Subsidy optimizes ψ_2 and keeps ψ_1 and ψ_3 fixed; and so on. For GV Ban, t^g indicates the year in which the ban is implemented. For GV Quota, $\mathcal{G}$ is the cumulative allowed production of gas vehicles. G^T and X^T are the values at the end of the finite horizon.

Table H: Learning by Doing $\epsilon_{Gp_X} = 5.5$

Policy	Optimal Parameter	Deadweight Loss ($ billions)	Transition Time t^e (Year)	t^g (Year)	Terminal State G^T	X^T
First Best	n.a.	0	2019.3	2019.8	3.2	129.5
BAU	n.a.	28.8	2021.0	n.a.	25.9	104.6
EV Subsidy	ψ_1= 931	20.0	2018.5	n.a.	15.0	119.3
EV Initial Price Subsidy	ψ_2= 2533	25.9	2018.9	n.a.	25.6	105.0
EV Decay Subsidy	ψ_3= -0.012	23.5	2018.8	n.a.	24.5	106.6
EV Two Parm Subsidy	ψ_1= 1673 ψ_2= -4393	17.8	2019.7	n.a.	6.7	130.6
GV Ban	t^g = 2018.6	16.7	2019.9	2018.6	3.5	129.7
GV Quota	$\mathcal{G}$ = 105	9.3	2018.3	2018.7	3.1	130.1
GV Flexible Quota	$\mathcal{G}$ = 105 κ= 0.0	9.3	2018.3	n.a.	3.1	130.1

Notes: For subsidy policies, the price path formula is $\tilde{c}_x = (c_g - \psi_1) + (21961 - \psi_2)e^{-(0.06-\psi_3)t}$, with default values $\psi_1 = 0$, $\psi_2 = 0$, $\psi_3 = 0$. The EV Two Parm Subsidy policy selects ψ_1 and ψ_2 to minimize deadweight loss and keeps ψ_3 fixed, the EV Subsidy policy optimizes ψ_1 and keeps ψ_2 and ψ_3 fixed; the EV Initial Price Subsidy policy optimizes ψ_2 and keeps ψ_1 and ψ_3 fixed; and so on. For GV Ban, t^g indicates the year in which the ban is implemented. For GV Quota, $\mathcal{G}$ is the cumulative allowed production of gas vehicles. G^T and X^T are the values at the end of the finite horizon.

J Learning by Doing

The second best analysis for learning by doing, in the $\epsilon_{Gp_X} = 5.5$ case, is shown in Table H.

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