

Online Appendix

Peer Road Pricing with Green Vehicle Exemptions:
Theory and Evidence

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A. Derivations

In this Appendix, we derive optimal congestion charges for (a) policies that exempt green vehicles, (b) policies that charge all vehicles, and (c) policies that charge different tolls for green vehicles versus brown vehicles. We also cover several related extensions, like adjusting optimal tolls to account for pre-existing policies that influence the marginal cost of driving.

A.1. Optimal congestion charges with green exemptions

We begin by taking first-order conditions of the consumer's problem (see equation 2):

$$\begin{aligned}
\frac{\partial B}{\partial n_g} &= 0 = \mu'_g[u_g^c(t_g^c) + u_g^o(t_g^o)] - (p^c + p_g l_g) v^c t_g^c - (p^o + p_g l_g) t_g^o v^o - c_g \\
\frac{\partial B}{\partial n_b} &= 0 = \mu'_b[u_b^c(t_b^c) + u_b^o(t_b^o)] - ((p^c + p_b l_b) v^c + \tau) t_b^c - (p^o + p_b l_b) t_b^o v^o - c_b \\
\frac{\partial B}{\partial t_b^c} &= 0 = \mu_b(n_b)[u_b'^c(t_b^c)] - n_b((p^c + p_b l_b) v^c + \tau) \\
\frac{\partial B}{\partial t_g^c} &= 0 = \mu_g(n_g)[u_g'^c(t_g^c)] - n_g(p^c + p_g l_g) v^c \\
\frac{\partial B}{\partial t_b^o} &= 0 = \mu_b(n_b)[u_b'^o(t_b^o)] - n_b(p^o + p_b l_b) v^o \\
\frac{\partial B}{\partial t_g^o} &= 0 = \mu_g(n_g)[u_g'^o(t_g^o)] - n_g(p^o + p_g l_g) v^o \\
\frac{\partial B}{\partial v^o} &= 0 = -n_g(p^o + p_g l_g) t_g^o - n_b(p^o + p_b l_b) t_b^o - r'(v^o) \\
\frac{\partial B}{\partial v^c} &= 0 = -n_g(p^c + p_g l_g) t_g^c - n_b(p^c + p_b l_b) t_b^c - r'(v^c).
\end{aligned}$$

The derivative of W , social welfare, with respect to congestion charge τ is:

$$\begin{aligned}
\frac{\partial W}{\partial \tau} = 0 = & \frac{\partial n_g}{\partial \tau} \left(\mu'_g[u_g^c(t_g^c) + u_g^o(t_g^o)] - (p^c + p_g l_g) v^c t_g^c - (p^o + p_g l_g) t_g^o v^o \right. \\
& \left. - c_g - (v^c t_g^c + v^o t_g^o) l_g \phi_g - v^c t_g^c \gamma^c - v^o t_g^o \gamma^o \right) \\
& + \frac{\partial n_b}{\partial \tau} \left(\mu'_b[u_b^c(t_b^c) + u_b^o(t_b^o)] - (p^c + p_b l_b) v^c t_b^c - (p^o + p_b l_b) t_b^o v^o \right. \\
& \left. - c_b - (v^c t_b^c + v^o t_b^o) l_b \phi_b - v^c t_b^c \gamma^c - v^o t_b^o \gamma^o \right) \\
& + \frac{\partial t_g^o}{\partial \tau} \left(\mu_g(n_g)[u_g^o] - n_g(p^o + p_g l_g) v^o - n_g v^o l_g \phi_g - n_g v^o \gamma^o \right) \\
& + \frac{\partial t_g^c}{\partial \tau} \left(\mu_g(n_g)[u_g^c] - n_g(p^c + p_g l_g) v^c - n_g v^c l_g \phi_g - n_g v^c \gamma^c \right) \\
& + \frac{\partial t_b^o}{\partial \tau} \left(\mu_b(n_b)[u_b^o] - n_b(p^o + p_b l_b) v^o - n_b v^o l_b \phi_b - n_b v^o \gamma^o \right) \\
& + \frac{\partial t_b^c}{\partial \tau} \left(\mu_b(n_b)[u_b^c] - n_b(p^c + p_b l_b) v^c - n_b v^c l_b \phi_b - n_b v^c \gamma^c \right) \\
& + \frac{\partial v^c}{\partial \tau} \left(-n_g(p^c + p_g l_g) t_g^c - n_b(p^c + p_b l_b) t_b^c - r'(v^c) \right. \\
& \left. - n_b t_b^c l_b \phi_b - n_g t_g^c l_g \phi_g - (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\
& + \frac{\partial v^o}{\partial \tau} \left(-n_g(p^o + p_g l_g) t_g^o - n_b(p^o + p_b l_b) t_b^o - r'(v^o) \right. \\
& \left. - n_b t_b^o l_b \phi_b - n_g t_g^o l_g \phi_g - (n_b t_b^o + n_g t_g^o) \gamma^o \right).
\end{aligned}$$

The social planner chooses the congestion charge, taking into account how the representative agent will respond. Plugging in the first-order conditions of the representative agent, we have:

$$\begin{aligned}
0 = & \frac{\partial n_g}{\partial \tau} \left(-(v^c t_g^c + v^o t_g^o) l_g \phi_g - v^c t_g^c \gamma^c - v^o t_g^o \gamma^o \right) \\
& + \frac{\partial n_b}{\partial \tau} \left(\tau t_b^c - (v^c t_b^c + v^o t_b^o) l_b \phi_b - v^c t_b^c \gamma^c - v^o t_b^o \gamma^o \right) \\
& + \frac{\partial t_g^o}{\partial \tau} \left(-n_g v^o l_g \phi_g - n_g v^o \gamma^o \right) \\
& + \frac{\partial t_g^c}{\partial \tau} \left(-n_g v^c l_g \phi_g - n_g v^c \gamma^c \right) \\
& + \frac{\partial t_b^o}{\partial \tau} \left(-n_b v^o l_b \phi_b - n_b v^o \gamma^o \right) \\
& + \frac{\partial t_b^c}{\partial \tau} \left(n_b \tau - n_b v^c l_b \phi_b - n_b v^c \gamma^c \right) \\
& + \frac{\partial v^c}{\partial \tau} \left(-n_b t_b^c l_b \phi_b - n_g t_g^c l_g \phi_g - (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\
& + \frac{\partial v^o}{\partial \tau} \left(-n_b t_b^o l_b \phi_b - n_g t_g^o l_g \phi_g - (n_b t_b^o + n_g t_g^o) \gamma^o \right).
\end{aligned}$$

Solving this equation for the optimal congestion charge τ results in Proposition 1.

A.2. Writing the optimal congestion charge in terms of policy responses

Here, we rephrase the optimal congestion tax for policies that exempt green vehicles in terms of observable statistics and policy responses.

Externalities: First, we define the annual emission and congestion externalities per vehicle ($\tilde{\phi}$ and $\tilde{\gamma}$) as the product of the emission and congestion damages per kilometer traveled and the kilometers traveled by each vehicle. We calculate this figure separately for green and brown vehicles. The total emission and congestion externalities (expressed in €) per vehicle per year are:

$$\tilde{\phi}_g = (v^c t_g^c + v^o t_g^o) l_g \phi_g \quad \tilde{\phi}_b = (v^c t_b^c + v^o t_b^o) l_b \phi_b \quad (\text{A1})$$

$$\tilde{\gamma}_g = v^c t_g^c \gamma^c + v^o t_g^o \gamma^o \quad \tilde{\gamma}_b = v^c t_b^c \gamma^c + v^o t_b^o \gamma^o \quad (\text{A2})$$

Second, we define emission and congestion externalities per fleet-trip ($\bar{\phi}$ and $\bar{\gamma}$) as the product of the per-kilometer externality, the number of vehicles, and the average trip distance. We calculate these parameters separately by trip type (inside versus outside) and vehicle type (green or brown), leaving us with eight total parameters:

$$\bar{\phi}_g^c = n_g v^c l_g \phi_g \quad \bar{\phi}_b^c = n_b v^c l_b \phi_b \quad \bar{\phi}_g^o = n_g v^o l_g \phi_g \quad \bar{\phi}_b^o = n_b v^o l_b \phi_b \quad (\text{A3})$$

$$\bar{\gamma}_g^c = n_g v^c \gamma^c \quad \bar{\gamma}_b^c = n_b v^c \gamma^c \quad \bar{\gamma}_g^o = n_g v^o \gamma^o \quad \bar{\gamma}_b^o = n_b v^o \gamma^o \quad (\text{A4})$$

Third, we define emission and congestion externalities per fleet kilometer traveled ($\hat{\phi}$ and $\hat{\gamma}$) as the product of the per-kilometer externalities, the number of vehicles, and the number of trips taken. We calculate this parameter separately by trip type (inside versus outside) and vehicle type (green versus brown), leaving us with four parameters:

$$\hat{\phi}^c = n_b t_b^c l_b \phi_b + n_g t_g^c l_g \phi_g \quad \hat{\phi}^o = n_b t_b^o l_b \phi_b + n_g t_g^o l_g \phi_g \quad (\text{A5})$$

$$\hat{\gamma}^c = (n_b t_b^c + n_g t_g^c) \gamma^c \quad \hat{\gamma}^o = (n_b t_b^o + n_g t_g^o) \gamma^o \quad (\text{A6})$$

Policy responses: We discretize the derivatives of the fleet composition, the number of trips, and commuting distances with respect to the congestion charge and scale them by the common denominator in equation (4) ($\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b$) as follows:

$$\underline{\Delta} N_g = \frac{1}{(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b)} \frac{\partial n_g}{\partial \tau} = \frac{1}{(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b)} \frac{\Delta n_g}{\Delta \tau} = \frac{\Delta n_g}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \quad (\text{A7})$$

$$\underline{\Delta}N_b = \frac{1}{\left(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b\right)} \frac{\partial n_b}{\partial \tau} = \frac{1}{\left(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b\right)} \frac{\Delta n_b}{\Delta \tau} = \frac{\Delta n_b}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \quad (\text{A8})$$

$$\underline{\Delta}T_g^o = \frac{1}{\left(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b\right)} \frac{\partial t_g^o}{\partial \tau} = \frac{1}{\left(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b\right)} \frac{\Delta t_g^o}{\Delta \tau} = \frac{\Delta t_g^o}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \quad (\text{A9})$$

$$\underline{\Delta}T_g^c = \frac{1}{\left(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b\right)} \frac{\partial t_g^c}{\partial \tau} = \frac{1}{\left(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b\right)} \frac{\Delta t_g^c}{\Delta \tau} = \frac{\Delta t_g^c}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \quad (\text{A10})$$

$$\underline{\Delta}T_b^o = \frac{1}{\left(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b\right)} \frac{\partial t_b^o}{\partial \tau} = \frac{1}{\left(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b\right)} \frac{\Delta t_b^o}{\Delta \tau} = \frac{\Delta t_b^o}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \quad (\text{A11})$$

$$\underline{\Delta}V^c = \frac{1}{\left(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b\right)} \frac{\partial v^c}{\partial \tau} = \frac{1}{\left(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b\right)} \frac{\Delta v^c}{\Delta \tau} = \frac{\Delta v^c}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \quad (\text{A12})$$

$$\underline{\Delta}V^o = \frac{1}{\left(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b\right)} \frac{\partial v^o}{\partial \tau} = \frac{1}{\left(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b\right)} \frac{\Delta v^o}{\Delta \tau} = \frac{\Delta v^o}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \quad (\text{A13})$$

Plugging in the converted externalities and discretized responses to the congestion charges allows us to rearrange equation (4) as equation (5).

Note that because the derivatives in the numerator and the denominator of each response include the change in the congestion charge ($\Delta\tau$), this term cancels out in all equations. Therefore, equation (5) depends only on the responsiveness to taxes, not the magnitude of the tax change used to estimate these empirical objects.

Relatedly, recall that equations (4) and (5) are valid for externalities and policy responses evaluated *at the optimum*. In Section I, we discuss the possibility of non-linear externalities. A more subtle point is that the “ $\underline{\Delta}$ ” components of equation (5) — which rely on ratios of policy responses — may differ at versus away from the optimum.

Even if the components of the $\underline{\Delta}$ terms are not invariant, there are a number of scenarios where the ratios will be similar at versus away from the optimum. The most general is if the demand for urban travel exhibits constant diversion ratios.²¹ To see this, note that the terms can be regrouped by externality type rather than by behavioral margin. For example, collecting all terms in the numerator of equation (4) that are multiplied by γ^c from green vehicles yields:

$$\gamma^c \left(\frac{\partial n_g}{\partial \tau} v^c t_g^c + n_g v^c \frac{\partial t_g^c}{\partial \tau} + n_g t_g^c \frac{\partial v^c}{\partial \tau} \right) \quad (\text{A14})$$

21. See Conlon and Mortimer (2021) for an overview of diversion ratios and their properties in demand systems.

These three terms come from a product rule in the derivation of the optimal tax formula:

$$\gamma^c \cdot \frac{\partial}{\partial \tau} (n_g v^c t_g^c) \quad (\text{A15})$$

Dividing by the denominator of the substitution term, the green cordon congestion contribution is:

$$\gamma^c \cdot \frac{\frac{\partial}{\partial \tau} (n_g v^c t_g^c)}{\frac{\partial}{\partial \tau} (n_b t_b^c)} \quad (\text{A16})$$

This is a ratio of derivatives — changes in total green cordon VKT over changes in total brown cordon trips. Each externality type has an analogous expression. In each case, the relevant object is a ratio of total derivatives of composite variables — green cordon VKT, total green VKT, brown outside VKT, etc. — to the derivative of total brown cordon trips. Denoting any such composite variable as $Y(\tau)$ and total brown cordon trips as $Q_b^c(\tau) \equiv n_b(\tau) t_b^c(\tau)$, the ratio of interest is $\frac{\partial Y / \partial \tau}{\partial Q_b^c / \partial \tau}$. Differentiating with respect to τ and applying the quotient rule, this ratio is constant in τ if and only if:

$$\frac{\frac{\partial^2 Y}{\partial \tau^2}}{\frac{\partial Y}{\partial \tau}} = \frac{\frac{\partial^2 Q_b^c}{\partial \tau^2}}{\frac{\partial Q_b^c}{\partial \tau}} \quad (\text{A17})$$

That is, each composite variable must have the same ratio of first to second derivatives as total brown cordon trips. This is equivalent to requiring that each composite variable is an affine function of the quantity of brown trips. Continuing with our example of congestion caused by green cordon trips, the green cordon congestion ratio is constant if and only if $n_g(\tau) v^c(\tau) t_g^c(\tau) = \alpha + \beta \cdot n_b(\tau) t_b^c(\tau)$, for some constants α and β .

Note that this condition is significantly weaker than requiring that responses be linear in τ . It requires only that the composite variable responses — total VKT by vehicle and trip type — maintain a proportional relationship to the total brown cordon trip response. There will be constant diversion ratios if, for example, all composite response functions are linear, if they are all quadratic, or if they are all of the form $f(\tau) = \alpha + b e^{\beta \tau}$.

A.3. Special cases

The optimal congestion charge on non-exempt vehicles described in equation (4) has several special cases that provide insight into how optimal congestion tolls reflect the consumer's different margins of response. We highlight four special cases of particular interest.

No congestion externalities ($\gamma^c = \gamma^o = 0$):

$$\tau^{emission} = \Delta N_g \cdot (\widetilde{\phi}_g) + \Delta N_b \cdot \widetilde{\phi}_b + \Delta T \cdot \bar{\phi} + \Delta V^c \cdot \hat{\phi}^c + \Delta V^o \cdot \hat{\phi}^o + \bar{\phi}_b^c \quad (A18)$$

No emission externalities ($\phi_g = \phi_b = 0$):

$$\tau^{congestion} = \Delta N_g \cdot (\widetilde{\gamma}_g) + \Delta N_b \cdot \widetilde{\gamma}_b + \Delta T \cdot \bar{\gamma} + \Delta V^c \cdot \hat{\gamma}^c + \Delta V^o \cdot \hat{\gamma}^o + \bar{\gamma}_b^c \quad (A19)$$

No trip leakage ($\frac{\partial t^o}{\partial \tau} = 0$):

$$\begin{aligned} \tau^{no\ leakage} = & \frac{1}{(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b)} \left(\frac{\partial n_g}{\partial \tau} \left((v^c t_g^c + v^o t_g^o) l_g \phi_g + v^c t_g^c \gamma^c + v^o t_g^o \gamma^o \right) \right. \\ & + \frac{\partial n_b}{\partial \tau} \left((v^c t_b^c + v^o t_b^o) l_b \phi_b + v^c t_b^c \gamma^c + v^o t_b^o \gamma^o \right) \\ & + \frac{\partial t_g^c}{\partial \tau} \left(n_g v^c (l_g \phi_g + \gamma^c) \right) + \frac{\partial t_b^c}{\partial \tau} \left(n_b v^c (l_b \phi_b + \gamma^c) \right) \\ & + \frac{\partial v^c}{\partial \tau} \left(n_b t_b^c l_b \phi_b + n_g t_g^c l_g \phi_g + (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\ & \left. + \frac{\partial v^o}{\partial \tau} \left(n_b t_b^o l_b \phi_b + n_g t_g^o l_g \phi_g + (n_b t_b^o + n_g t_g^o) \gamma^o \right) \right) \end{aligned} \quad (A20)$$

Pre-existing policies: Here, there are two pre-existing policies that interact with congestion pricing. First, in some settings, existing environmental regulations already partially internalize the per-kilometer pollution externalities associated with driving brown vehicles. We, therefore, replace the brown vehicle emissions externalities, ϕ_b , with the uninternalized externality, $\mathring{\phi}_b$. Second, depending on the setting, green vehicles may be subsidized. To account for existing subsidies, we include a term, $\mathring{s}$, that acts to reduce the cost of purchasing a green vehicle. Tracing these changes through the derivation of Proposition 1 yields the following optimal tax formula, which also accounts for these two types of pre-existing regulation:

$$\begin{aligned}
\tau^{policies} = & \frac{1}{\left(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b\right)} \left(\frac{\partial n_g}{\partial \tau} \left((v^c t_g^c + v^o t_g^o) l_g \phi_g + v^c t_g^c \gamma^c + v^o t_g^o \gamma^o + \mathring{s} \right) \right. \\
& + \frac{\partial n_b}{\partial \tau} \left((v^c t_b^c + v^o t_b^o) l_b \mathring{\phi}_b + v^c t_b^c \gamma^c + v^o t_b^o \gamma^o \right) \\
& + \frac{\partial t_g^o}{\partial \tau} \left(n_g v^o (l_g \phi_g + \gamma^o) \right) + \frac{\partial t_g^c}{\partial \tau} \left(n_g v^c (l_g \phi_g + \gamma^c) \right) \\
& + \frac{\partial t_b^o}{\partial \tau} \left(n_b v^o (l_b \mathring{\phi}_b + \gamma^o) \right) + \frac{\partial t_b^c}{\partial \tau} \left(n_b v^c (l_b \mathring{\phi}_b + \gamma^c) \right) \\
& + \frac{\partial v^c}{\partial \tau} \left(n_b t_b^c l_b \mathring{\phi}_b + n_g t_g^c l_g \phi_g + (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\
& \left. + \frac{\partial v^o}{\partial \tau} \left(n_b t_b^o l_b \mathring{\phi}_b + n_g t_g^o l_g \phi_g + (n_b t_b^o + n_g t_g^o) \gamma^o \right) \right) \quad (A21)
\end{aligned}$$

A.4. Optimal congestion charges without exemptions

This section shows the steps in deriving the optimal “uniform” congestion tax. That is, the optimal charge, τ^u , levied on all vehicles entering the congestion zone without any exemptions. We begin by taking first-order conditions of the consumer’s problem (see equation 2). This process is the same as the process for deriving the optimal tax with exemptions, but the congestion tax now enters the representative consumer’s utility whenever either type of vehicle, green or brown, takes a cordon zone trip.

$$\begin{aligned}
\frac{\partial B}{\partial n_g} &= 0 = \mu'_g[u_g^c(t_g^c) + u_g^o(t_g^o)] - ((p^c + p_g l_g)v^c + \tau^u)t_g^c - (p^o + p_g l_g)t_g^o v^o - c_g \\
\frac{\partial B}{\partial n_b} &= 0 = \mu'_b[u_b^c(t_b^c) + u_b^o(t_b^o)] - ((p^c + p_b l_b)v^c + \tau^u)t_b^c - (p^o + p_b l_b)t_b^o v^o - c_b \\
\frac{\partial B}{\partial t_b^c} &= 0 = \mu_b(n_b)[u_b'^c(t_b^c)] - n_b((p^c + p_b l_b)v^c + \tau^u) \\
\frac{\partial B}{\partial t_g^c} &= 0 = \mu_g(n_g)[u_g'^c(t_g^c)] - n_g((p^c + p_g l_g)v^c + \tau^u) \\
\frac{\partial B}{\partial t_b^o} &= 0 = \mu_b(n_b)[u_b'^o(t_b^o)] - n_b(p^o + p_b l_b)v^o \\
\frac{\partial B}{\partial t_g^o} &= 0 = \mu_g(n_g)[u_g'^o(t_g^o)] - n_g(p^o + p_g l_g)v^o \\
\frac{\partial B}{\partial v^o} &= 0 = -n_g(p^o + p_g l_g)t_g^o - n_b(p^o + p_b l_b)t_b^o - r'(v^o) \\
\frac{\partial B}{\partial v^c} &= 0 = -n_g(p^c + p_g l_g)t_g^c - n_b(p^c + p_b l_b)t_b^c - r'(v^c)
\end{aligned}$$

The derivative of W , social welfare, with respect to the uniform congestion charge τ^u is:

$$\begin{aligned}
\frac{\partial W}{\partial \tau^u} = 0 = & \frac{\partial n_g}{\partial \tau^u} \left(\mu'_g[u_g^c(t_g^c) + u_g^o(t_g^o)] - (p^c + p_g l_g) v^c t_g^c - (p^o + p_g l_g) t_g^o v^o \right. \\
& \left. - c_g - (v^c t_g^c + v^o t_g^o) l_g \phi_g - v^c t_g^c \gamma^c - v^o t_g^o \gamma^o \right) \\
& + \frac{\partial n_b}{\partial \tau^u} \left(\mu'_b[u_b^c(t_b^c) + u_b^o(t_b^o)] - (p^c + p_b l_b) v^c t_b^c - (p^o + p_b l_b) t_b^o v^o \right. \\
& \left. - c_b - (v^c t_b^c + v^o t_b^o) l_b \phi_b - v^c t_b^c \gamma^c - v^o t_b^o \gamma^o \right) \\
& + \frac{\partial t_g^o}{\partial \tau^u} \left(\mu_g(n_g)[u_g^o] - n_g(p^o + p_g l_g) v^o - n_g v^o l_g \phi_g - n_g v^o \gamma^o \right) \\
& + \frac{\partial t_g^c}{\partial \tau^u} \left(\mu_g(n_g)[u_g^c] - n_g(p^c + p_g l_g) v^c - n_g v^c l_g \phi_g - n_g v^c \gamma^c \right) \\
& + \frac{\partial t_b^o}{\partial \tau^u} \left(\mu_b(n_b)[u_b^o] - n_b(p^o + p_b l_b) v^o - n_b v^o l_b \phi_b - n_b v^o \gamma^o \right) \\
& + \frac{\partial t_b^c}{\partial \tau^u} \left(\mu_b(n_b)[u_b^c] - n_b(p^c + p_b l_b) v^c - n_b v^c l_b \phi_b - n_b v^c \gamma^c \right) \\
& + \frac{\partial v^c}{\partial \tau^u} \left(-n_g(p^c + p_g l_g) t_g^c - n_b(p^c + p_b l_b) t_b^c - r'(v^c) \right. \\
& \left. - n_b t_b^c l_b \phi_b - n_g t_g^c l_g \phi_g - (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\
& + \frac{\partial v^o}{\partial \tau^u} \left(-n_g(p^o + p_g l_g) t_g^o - n_b(p^o + p_b l_b) t_b^o - r'(v^o) \right. \\
& \left. - n_b t_b^o l_b \phi_b - n_g t_g^o l_g \phi_g - (n_b t_b^o + n_g t_g^o) \gamma^o \right)
\end{aligned}$$

The social planner chooses the congestion charge, taking into account how the representative agent will respond (see equation 2). Plugging in the first-order conditions of the representative agent, we have:

$$\begin{aligned}
0 = & \frac{\partial n_g}{\partial \tau^u} \left(\tau^u t_g^c - (v^c t_g^c + v^o t_g^o) l_g \phi_g - v^c t_g^c \gamma^c - v^o t_g^o \gamma^o \right) \\
& + \frac{\partial n_b}{\partial \tau^u} \left(\tau^u t_b^c - (v^c t_b^c + v^o t_b^o) l_b \phi_b - v^c t_b^c \gamma^c - v^o t_b^o \gamma^o \right) \\
& + \frac{\partial t_g^o}{\partial \tau^u} \left(-n_g v^o l_g \phi_g - n_g v^o \gamma^o \right) \\
& + \frac{\partial t_g^c}{\partial \tau^u} \left(n_g \tau^u - n_g v^c l_g \phi_g - n_g v^c \gamma^c \right) \\
& + \frac{\partial t_b^o}{\partial \tau^u} \left(-n_b v^o l_b \phi_b - n_b v^o \gamma^o \right) \\
& + \frac{\partial t_b^c}{\partial \tau^u} \left(n_b \tau^u - n_b v^c l_b \phi_b - n_b v^c \gamma^c \right) \\
& + \frac{\partial v^c}{\partial \tau^u} \left(-n_b t_b^c l_b \phi_b - n_g t_g^c l_g \phi_g - (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\
& + \frac{\partial v^o}{\partial \tau^u} \left(-n_b t_b^o l_b \phi_b - n_g t_g^o l_g \phi_g - (n_b t_b^o + n_g t_g^o) \gamma^o \right)
\end{aligned}$$

Solving this equation for the optimal uniform congestion charge τ^u yields:

$$\begin{aligned}
\tau^u = & \frac{1}{\left(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b + \frac{\partial n_g}{\partial \tau} t_g^c + \frac{\partial t_g^c}{\partial \tau} n_g \right)} \left(\frac{\partial n_g}{\partial \tau} \left((v^c t_g^c + v^o t_g^o) l_g \phi_g + v^c t_g^c \gamma^c + v^o t_g^o \gamma^o \right) \right. \\
& + \frac{\partial n_b}{\partial \tau} \left((v^c t_b^c + v^o t_b^o) l_b \phi_b + v^c t_b^c \gamma^c + v^o t_b^o \gamma^o \right) \\
& + \frac{\partial t_g^o}{\partial \tau} \left(n_g v^o (l_g \phi_g + \gamma^o) \right) + \frac{\partial t_g^c}{\partial \tau} \left(n_g v^c (l_g \phi_g + \gamma^c) \right) \\
& + \frac{\partial t_b^o}{\partial \tau} \left(n_b v^o (l_b \phi_b + \gamma^o) \right) + \frac{\partial t_b^c}{\partial \tau} \left(n_b v^c (l_b \phi_b + \gamma^c) \right) \\
& + \frac{\partial v^c}{\partial \tau} \left(n_b t_b^c l_b \phi_b + n_g t_g^c l_g \phi_g + (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\
& \left. + \frac{\partial v^o}{\partial \tau} \left(n_b t_b^o l_b \phi_b + n_g t_g^o l_g \phi_g + (n_b t_b^o + n_g t_g^o) \gamma^o \right) \right) \quad (\text{A22})
\end{aligned}$$

A.5. The optimal differentiated congestion charge

This section shows the steps in deriving the optimal differentiated congestion charge, which sets different tolls for green (τ_g) and brown vehicles (τ_b) entering the congestion zone. The representative consumer's optimization problem is to pick the optimal fleet size for each vehicle type (i.e., n_g , n_b), the optimal number of trips in each vehicle type completing the kind of trip (i.e., t_g^c , t_g^o , t_b^c , t_b^o), and the vehicle kilometers traveled for each trip (i.e., v^c , v^o) to maximize consumer welfare B given the congestion charge for green (τ_g) and brown vehicles (τ_b). The representative agent's problem is:

$$\begin{aligned}
 \max_{n_g, n_b, t_g^c, t_g^o, t_b^c, t_b^o, v^c, v^o} B = & \underbrace{\mu_g(n_g)[u_g^c(t_g^c) + u_g^o(t_g^o)]}_{\text{utility from green trips}} - \underbrace{n_g((p^c + p_g l_g)v^c + \tau_g)t_g^c - n_g(p^o + p_g l_g)v^o t_g^o}_{\text{utility cost of green trips}} \\
 & + \underbrace{\mu_b(n_b)[u_b^c(t_b^c) + u_b^o(t_b^o)]}_{\text{utility from brown trips}} - \underbrace{n_b((p^c + p_b l_b)v^c + \tau_b)t_b^c - n_b(p^o + p_b l_b)v^o t_b^o}_{\text{utility cost of brown trips}} \\
 & - \underbrace{n_b c_b - n_g c_g}_{\text{cost of vehicles}} - \underbrace{r^c(v^c) - r^o(v^o)}_{\text{cost of location choice}} + y. \tag{A23}
 \end{aligned}$$

The consumer's first-order conditions are:

$$\begin{aligned}
 \frac{\partial B}{\partial n_g} = 0 &= \mu'_g[u_g^c(t_g^c) + u_g^o(t_g^o)] - ((p^c + p_g l_g)v^c + \tau_g)t_g^c - (p^o + p_g l_g)t_g^o v^o - c_g \\
 \frac{\partial B}{\partial n_b} = 0 &= \mu'_b[u_b^c(t_b^c) + u_b^o(t_b^o)] - ((p^c + p_b l_b)v^c + \tau_b)t_b^c - (p^o + p_b l_b)t_b^o v^o - c_b \\
 \frac{\partial B}{\partial t_b^c} = 0 &= \mu_b(n_b)[u_b^c(t_b^c)] - n_b((p^c + p_b l_b)v^c + \tau_b) \\
 \frac{\partial B}{\partial t_g^c} = 0 &= \mu_g(n_g)[u_g^c(t_g^c)] - n_g((p^c + p_g l_g)v^c + \tau_g) \\
 \frac{\partial B}{\partial t_b^o} = 0 &= \mu_b(n_b)[u_b^o(t_b^o)] - n_b(p^o + p_b l_b)v^o \\
 \frac{\partial B}{\partial t_g^o} = 0 &= \mu_g(n_g)[u_g^o(t_g^o)] - n_g(p^o + p_g l_g)v^o \\
 \frac{\partial B}{\partial v^o} = 0 &= -n_g(p^o + p_g l_g)t_g^o - n_b(p^o + p_b l_b)t_b^o - r'(v^o) \\
 \frac{\partial B}{\partial v^c} = 0 &= -n_g(p^c + p_g l_g)t_g^c - n_b(p^c + p_b l_b)t_b^c - r'(v^c).
 \end{aligned}$$

The social planner's problem is to maximize consumer welfare $B_{-\tau}$ from equation (A23) by setting congestion charge for green (τ_g) and brown vehicles (τ_b) entering the congestion zone:

$$\begin{aligned} \max_{\tau_g, \tau_b} W = B_{-\tau} & - \underbrace{n_b(v^c t_b^c + v^o t_b^o) l_b \phi_b}_{\text{emission from brown trips}} - \underbrace{n_g(v^c t_g^c + v^o t_g^o) l_g \phi_g}_{\text{emission from green trips}} \\ & - \underbrace{(n_b v^c t_b^c + n_g v^c t_g^c) \gamma^c}_{\text{congestion from inside trips}} - \underbrace{(n_b v^o t_b^o + n_g v^o t_g^o) \gamma^o}_{\text{congestion from outside trips}}. \end{aligned} \quad (\text{A24})$$

The derivative of W with respect to congestion charge on brown vehicles τ_b is:

$$\begin{aligned} \frac{\partial W}{\partial \tau_b} = & \frac{\partial n_g}{\partial \tau_b} \left(\mu'_g[u_g^c(t_g^c) + u_g^o(t_g^o)] - (p^c + p_g l_g) v^c t_g^c - (p^o + p_g l_g) t_g^o v^o \right. \\ & \left. - c_g - (v^c t_g^c + v^o t_g^o) l_g \phi_g - v^c t_g^c \gamma^c - v^o t_g^o \gamma^o \right) \\ & + \frac{\partial n_b}{\partial \tau_b} \left(\mu'_b[u_b^c(t_b^c) + u_b^o(t_b^o)] - (p^c + p_b l_b) v^c t_b^c - (p^o + p_b l_b) t_b^o v^o \right. \\ & \left. - c_b - (v^c t_b^c + v^o t_b^o) l_b \phi_b - v^c t_b^c \gamma^c - v^o t_b^o \gamma^o \right) \\ & + \frac{\partial t_g^o}{\partial \tau_b} \left(\mu_g(n_g)[u'_g] - n_g(p^o + p_g l_g) v^o - n_g v^o l_g \phi_g - n_g v^o \gamma^o \right) \\ & + \frac{\partial t_g^c}{\partial \tau_b} \left(\mu_g(n_g)[u'_g] - n_g(p^c + p_g l_g) v^c - n_g v^c l_g \phi_g - n_g v^c \gamma^c \right) \\ & + \frac{\partial t_b^o}{\partial \tau_b} \left(\mu_b(n_b)[u'_b] - n_b(p^o + p_b l_b) v^o - n_b v^o l_b \phi_b - n_b v^o \gamma^o \right) \\ & + \frac{\partial t_b^c}{\partial \tau_b} \left(\mu_b(n_b)[u'_b] - n_b(p^c + p_b l_b) v^c - n_b v^c l_b \phi_b - n_b v^c \gamma^c \right) \\ & + \frac{\partial v^c}{\partial \tau_b} \left(-n_g(p^c + p_g l_g) t_g^c - n_b(p^c + p_b l_b) t_b^c - r'(v^c) \right. \\ & \left. - n_b t_b^c l_b \phi_b - n_g t_g^c l_g \phi_g - (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\ & + \frac{\partial v^o}{\partial \tau_b} \left(-n_g(p^o + p_g l_g) t_g^o - n_b(p^o + p_b l_b) t_b^o - r'(v^o) \right. \\ & \left. - n_b t_b^o l_b \phi_b - n_g t_g^o l_g \phi_g - (n_b t_b^o + n_g t_g^o) \gamma^o \right). \end{aligned}$$

The derivative of W with respect to congestion charge on green vehicles τ_g is:

$$\begin{aligned}
\frac{\partial W}{\partial \tau_g} = & \frac{\partial n_g}{\partial \tau_g} \left(\mu'_g[u_g^c(t_g^c) + u_g^o(t_g^o)] - (p^c + p_g l_g) v^c t_g^c - (p^o + p_g l_g) t_g^o v^o \right. \\
& \left. - c_g - (v^c t_g^c + v^o t_g^o) l_g \phi_g - v^c t_g^c \gamma^c - v^o t_g^o \gamma^o \right) \\
& + \frac{\partial n_b}{\partial \tau_g} \left(\mu'_b[u_b^c(t_b^c) + u_b^o(t_b^o)] - (p^c + p_b l_b) v^c t_b^c - (p^o + p_b l_b) t_b^o v^o \right. \\
& \left. - c_b - (v^c t_b^c + v^o t_b^o) l_b \phi_b - v^c t_b^c \gamma^c - v^o t_b^o \gamma^o \right) \\
& + \frac{\partial t_g^o}{\partial \tau_g} \left(\mu_g(n_g)[u_g^o] - n_g(p^o + p_g l_g) v^o - n_g v^o l_g \phi_g - n_g v^o \gamma^o \right) \\
& + \frac{\partial t_g^c}{\partial \tau_g} \left(\mu_g(n_g)[u_g^c] - n_g(p^c + p_g l_g) v^c - n_g v^c l_g \phi_g - n_g v^c \gamma^c \right) \\
& + \frac{\partial t_b^o}{\partial \tau_g} \left(\mu_b(n_b)[u_b^o] - n_b(p^o + p_b l_b) v^o - n_b v^o l_b \phi_b - n_b v^o \gamma^o \right) \\
& + \frac{\partial t_b^c}{\partial \tau_g} \left(\mu_b(n_b)[u_b^c] - n_b(p^c + p_b l_b) v^c - n_b v^c l_b \phi_b - n_b v^c \gamma^c \right) \\
& + \frac{\partial v^c}{\partial \tau_g} \left(-n_g(p^c + p_g l_g) t_g^c - n_b(p^c + p_b l_b) t_b^c - r'(v^c) \right. \\
& \left. - n_b t_b^c l_b \phi_b - n_g t_g^c l_g \phi_g - (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\
& + \frac{\partial v^o}{\partial \tau_g} \left(-n_g(p^o + p_g l_g) t_g^o - n_b(p^o + p_b l_b) t_b^o - r'(v^o) \right. \\
& \left. - n_b t_b^o l_b \phi_b - n_g t_g^o l_g \phi_g - (n_b t_b^o + n_g t_g^o) \gamma^o \right).
\end{aligned}$$

The social planner chooses the congestion charge for green and brown vehicles, taking into account how the representative agent will respond. Plugging in the first-order conditions of the representative agent, we have:

$$\begin{aligned}
\frac{\partial W}{\partial \tau_b} = 0 = & \frac{\partial n_g}{\partial \tau_b} \left(\tau_g t_g^c - (v^c t_g^c + v^o t_g^o) l_g \phi_g - v^c t_g^c \gamma^c - v^o t_g^o \gamma^o \right) \\
& + \frac{\partial n_b}{\partial \tau_b} \left(\tau_b t_b^c - (v^c t_b^c + v^o t_b^o) l_b \phi_b - v^c t_b^c \gamma^c - v^o t_b^o \gamma^o \right) \\
& + \frac{\partial t_g^o}{\partial \tau_b} \left(-n_g v^o l_g \phi_g - n_g v^o \gamma^o \right) \\
& + \frac{\partial t_g^c}{\partial \tau_b} \left(n_g \tau_g - n_g v^c l_g \phi_g - n_g v^c \gamma^c \right) \\
& + \frac{\partial t_b^o}{\partial \tau_b} \left(-n_b v^o l_b \phi_b - n_b v^o \gamma^o \right) \\
& + \frac{\partial t_b^c}{\partial \tau_b} \left(n_b \tau_b - n_b v^c l_b \phi_b - n_b v^c \gamma^c \right) \\
& + \frac{\partial v^c}{\partial \tau_b} \left(-n_b t_b^c l_b \phi_b - n_g t_g^c l_g \phi_g - (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\
& + \frac{\partial v^o}{\partial \tau_b} \left(-n_b t_b^o l_b \phi_b - n_g t_g^o l_g \phi_g - (n_b t_b^o + n_g t_g^o) \gamma^o \right)
\end{aligned}$$

$$\begin{aligned}
\frac{\partial W}{\partial \tau_g} = 0 = & \frac{\partial n_g}{\partial \tau_g} \left(\tau_g t_g^c - (v^c t_g^c + v^o t_g^o) l_g \phi_g - v^c t_g^c \gamma^c - v^o t_g^o \gamma^o \right) \\
& + \frac{\partial n_b}{\partial \tau_g} \left(\tau_b t_b^c - (v^c t_b^c + v^o t_b^o) l_b \phi_b - v^c t_b^c \gamma^c - v^o t_b^o \gamma^o \right) \\
& + \frac{\partial t_g^o}{\partial \tau_g} \left(-n_g v^o l_g \phi_g - n_g v^o \gamma^o \right) \\
& + \frac{\partial t_g^c}{\partial \tau_g} \left(n_g \tau_g - n_g v^c l_g \phi_g - n_g v^c \gamma^c \right) \\
& + \frac{\partial t_b^o}{\partial \tau_g} \left(-n_b v^o l_b \phi_b - n_b v^o \gamma^o \right) \\
& + \frac{\partial t_b^c}{\partial \tau_g} \left(n_b \tau_b - n_b v^c l_b \phi_b - n_b v^c \gamma^c \right) \\
& + \frac{\partial v^c}{\partial \tau_g} \left(-n_b t_b^c l_b \phi_b - n_g t_g^c l_g \phi_g - (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\
& + \frac{\partial v^o}{\partial \tau_g} \left(-n_b t_b^o l_b \phi_b - n_g t_g^o l_g \phi_g - (n_b t_b^o + n_g t_g^o) \gamma^o \right).
\end{aligned}$$

Solving this system of equations gives the optimal charges for brown and green vehicles.

Proposition 2. *The second-best congestion charge on brown τ_b and green vehicles τ_g per crossing that address congestion and emission externalities through changes in the fleet composition, the number of trips, and the commuting distance are given by*

$$\tau_b^* = \frac{(c + da)}{(1 - db)} \quad (\text{A25})$$

$$\tau_g^* = a + b \frac{(c + da)}{(1 - db)}, \quad (\text{A26})$$

where a , b , c , and d are functions of derivatives of the congestion charges and the externalities. The expressions for a , b , c , and d are:

$$\begin{aligned} a = & \frac{1}{\frac{\partial n_g}{\partial \tau_g} t_g^c + \frac{\partial t_g^c}{\partial \tau_g} n_g} \left(\frac{\partial n_g}{\partial \tau_g} \left((v^c t_g^c + v^o t_g^o) l_g \phi_g + v^c t_g^c \gamma^c + v^o t_g^o \gamma^o \right) \right. \\ & + \frac{\partial n_b}{\partial \tau_g} \left((v^c t_b^c + v^o t_b^o) l_b \phi_b + v^c t_b^c \gamma^c + v^o t_b^o \gamma^o \right) \\ & + \frac{\partial t_g^o}{\partial \tau_g} \left(n_g v^o l_g \phi_g + n_g v^o \gamma^o \right) + \frac{\partial t_g^c}{\partial \tau_g} \left(n_g v^c l_g \phi_g + n_g v^c \gamma^c \right) \\ & + \frac{\partial t_b^o}{\partial \tau_g} \left(n_b v^o l_b \phi_b + n_b v^o \gamma^o \right) + \frac{\partial t_b^c}{\partial \tau_g} \left(n_b v^c l_b \phi_b + n_b v^c \gamma^c \right) \\ & + \frac{\partial v^c}{\partial \tau_g} \left(n_b t_b^c l_b \phi_b + n_g t_g^c l_g \phi_g + (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\ & \left. + \frac{\partial v^o}{\partial \tau_g} \left(n_b t_b^o l_b \phi_b + n_g t_g^o l_g \phi_g + (n_b t_b^o + n_g t_g^o) \gamma^o \right) \right) \\ b = & - \frac{\frac{\partial n_b}{\partial \tau_g} t_b^c + \frac{\partial t_b^c}{\partial \tau_g} n_b}{\frac{\partial n_g}{\partial \tau_g} t_g^c + \frac{\partial t_g^c}{\partial \tau_g} n_g} \\ c = & \frac{1}{\frac{\partial n_b}{\partial \tau_b} t_b^c + \frac{\partial t_b^c}{\partial \tau_b} n_b} \left(\frac{\partial n_g}{\partial \tau_b} \left((v^c t_g^c + v^o t_g^o) l_g \phi_g + v^c t_g^c \gamma^c + v^o t_g^o \gamma^o \right) \right. \\ & + \frac{\partial n_b}{\partial \tau_b} \left((v^c t_b^c + v^o t_b^o) l_b \phi_b + v^c t_b^c \gamma^c + v^o t_b^o \gamma^o \right) \\ & + \frac{\partial t_g^o}{\partial \tau_b} \left(n_g v^o l_g \phi_g + n_g v^o \gamma^o \right) + \frac{\partial t_g^c}{\partial \tau_b} \left(n_g v^c l_g \phi_g + n_g v^c \gamma^c \right) \\ & + \frac{\partial t_b^o}{\partial \tau_b} \left(n_b v^o l_b \phi_b + n_b v^o \gamma^o \right) + \frac{\partial t_b^c}{\partial \tau_b} \left(n_b v^c l_b \phi_b + n_b v^c \gamma^c \right) \\ & + \frac{\partial v^c}{\partial \tau_b} \left(n_b t_b^c l_b \phi_b + n_g t_g^c l_g \phi_g + (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\ & \left. + \frac{\partial v^o}{\partial \tau_b} \left(n_b t_b^o l_b \phi_b + n_g t_g^o l_g \phi_g + (n_b t_b^o + n_g t_g^o) \gamma^o \right) \right) \\ d = & - \frac{\frac{\partial t_g^c}{\partial \tau_b} n_g + \frac{\partial n_g}{\partial \tau_b} t_g^c}{\frac{\partial n_b}{\partial \tau_b} t_b^c + \frac{\partial t_b^c}{\partial \tau_b} n_b} \end{aligned}$$

This system of optimal taxes can inform decisions regarding congestion prices that vary by vehicle type. Specifically, a first-order question is whether EVs would be taxed at a positive level under a second-best tax that distinguishes only between conventional and EVs.

Proposition 2 holds two insights that speak to this question: First, if demand for brown vehicle ownerships and trips does not depend on the congestion charge levied on green vehicles, then green vehicles are taxed at a positive level under the second-best optimal tax scheme. Second, the optimal tax on green vehicles is decreasing in the pollution level of brown vehicles so long as sorting responses to congestion pricing are sufficiently small. We briefly explain each claim below.

First, if the cross-price elasticity between green taxes and both brown trip and brown vehicle purchases are zero and leakage is incomplete, then the optimal differentiated green tax from equation (A26) is greater than zero:

$$\begin{aligned}
0 = & \frac{\partial n_g}{\partial \tau_g} \left(\tau_g t_g^c - (v^c t_g^c + v^o t_g^o) l_g \phi_g - v^c t_g^c \gamma^c - v^o t_g^o \gamma^o \right) \\
& + \frac{\partial n_b}{\partial \tau_g} \left(\tau_b t_b^c - (v^c t_b^c + v^o t_b^o) l_b \phi_b - v^c t_b^c \gamma^c - v^o t_b^o \gamma^o \right) \\
& + \frac{\partial t_g^o}{\partial \tau_g} \left(-n_g v^o l_g \phi_g - n_g v^o \gamma^o \right) \\
& + \frac{\partial t_g^c}{\partial \tau_g} \left(n_g \tau_g - n_g v^c l_g \phi_g - n_g v^c \gamma^c \right) \\
& + \frac{\partial t_b^o}{\partial \tau_g} \left(-n_b v^o l_b \phi_b - n_b v^o \gamma^o \right) \\
& + \frac{\partial v^c}{\partial \tau_g} \left(-n_b t_b^c l_b \phi_b - n_g t_g^c l_g \phi_g - (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\
& + \frac{\partial v^o}{\partial \tau_g} \left(-n_b t_b^o l_b \phi_b - n_g t_g^o l_g \phi_g - (n_b t_b^o + n_g t_g^o) \gamma^o \right).
\end{aligned}$$

This allows us to rewrite the green tax as:

$$\begin{aligned}
\tau_g = & \frac{1}{\frac{\partial n_g}{\partial \tau_g} t_g^c + \frac{\partial t_g^c}{\partial \tau_g} n_g} \left(\frac{\partial n_g}{\partial \tau_g} \left((v^c t_g^c + v^o t_g^o) l_g \phi_g + v^c t_g^c \gamma^c + v^o t_g^o \gamma^o \right) \right. \\
& + \frac{\partial t_g^o}{\partial \tau_g} \left(n_g v^o l_g \phi_g + n_g v^o \gamma^o \right) \\
& + \frac{\partial t_g^c}{\partial \tau_g} \left(n_g v^c l_g \phi_g + n_g v^c \gamma^c \right) \\
& + \frac{\partial v^c}{\partial \tau_g} \left(n_b t_b^c l_b \phi_b + n_g t_g^c l_g \phi_g + (n_b t_b^c + n_g t_g^c) \gamma^c \right) \\
& \left. + \frac{\partial v^o}{\partial \tau_g} \left(n_b t_b^o l_b \phi_b + n_g t_g^o l_g \phi_g + (n_b t_b^o + n_g t_g^o) \gamma^o \right) \right).
\end{aligned}$$

It is sufficient but not necessary for trip leakage to be incomplete (i.e., the total damages induced by taking trips outside of the congestion zone are less than the externalities from reduced downtown trips, $|\frac{\partial t_g^o}{\partial \tau_g} (n_g v^o l_g \phi_g + n_g v^o \gamma^o)| < |\frac{\partial t_g^c}{\partial \tau_g} (n_g v^c l_g \phi_g + n_g v^c \gamma^c)|$) for the above expression of τ_g to be positive.

Intuitively, if these goods are neither substitutes nor complements, the system of equations collapses into two separate second-best tax problems for each vehicle type. As driving in green cars still causes congestion, the optimal tax on this type of vehicle is not zero. This zero cross-price elasticity scenario is not meant to be taken as a description; instead, it serves to show that the rationale for exempting green vehicles is weaker when they are weak substitutes for conventional fossil fuel vehicles.

Second, the cleaner the brown vehicle fleet, the more likely the optimal differentiated charge on green vehicles will be positive. Consider the scenario where both brown and green vehicle emissions approach zero. In this case, the only rationale for a negative tax on either vehicle type would be if leakage induced by the congestion pricing policy generated social damages greater than the social benefits from fewer downtown trips. In terms of the equations presented above, if leakage is incomplete (i.e., the increase in non-cordon externalities is smaller than the decrease in cordon-zone externalities) and own-price derivatives are negative, then (a) terms a and c will be unambiguously positive, (b) $0 < bd < 1$, and (c) both b and d are positive. This means that the taxes on both vehicle types will be positive.

B. Additional background on Stockholm's congestion pricing

In this section, we provide additional details on Stockholm's congestion pricing scheme as a complement to the context provided in Section II.

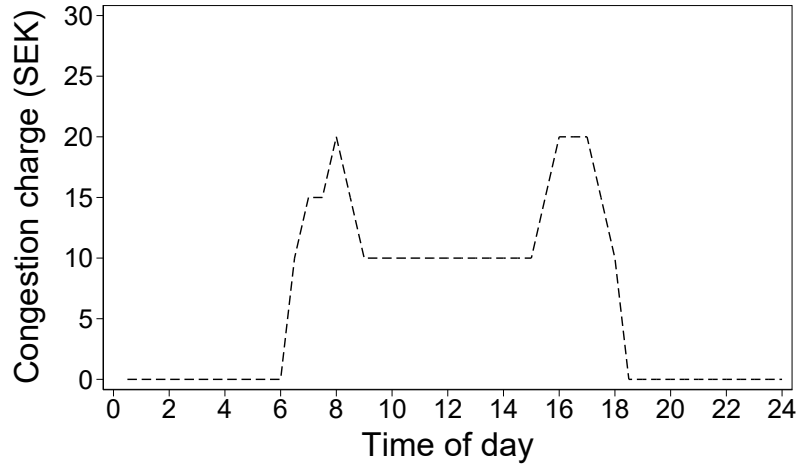


Figure B1: Congestion charges by time of the day in Stockholm, 2006-2015

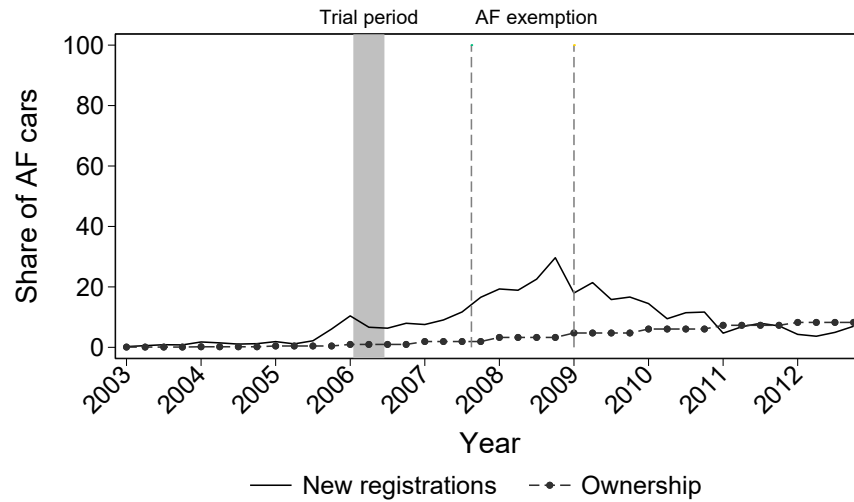


Figure B2: Share of new alternative fuel vehicles in Stockholm

Notes: This figure plots the quarterly share of new alternative fuel vehicle registrations (solid line) and the cumulative share of the alternative fuel vehicle stock (dashed line) in Stockholm from 2003 to 2012. The gray shaded region indicates the congestion trial period between January 2006 and July 2006. New alternative vehicles were exempt from the charge between August 2007 and December 2008 (gray dashed lines).

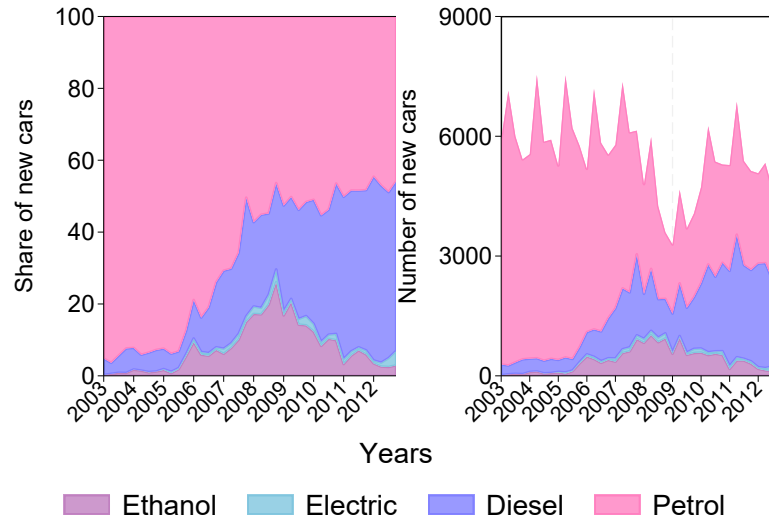


Figure B3: Newly registered cars in Stockholm

Notes: These figures display the share (Panel A) and the total number (Panel B) of new cars registered privately in Sweden between 2003 and 2012 by vehicle type and quarter of year.

Table B1: Summary statistics by commuter group in 2005

	Treated		Non-treated		Normalized Difference
	Mean	Std. Dev.	Mean	Std. Dev.	
Age	44.48	10.06	43.86	9.93	0.06
Female	0.37	0.48	0.25	0.43	0.25
Gross Salary (in tho.)	505.56	498.51	465.09	290.30	0.10
Disposable Income (in tho.)	256.83	422.31	230.80	149.78	0.08
Self-Employed	0.05	0.22	0.03	0.18	0.10
Married or Cohabitant	0.74	0.44	0.72	0.45	0.05
At Least 1 Child	0.37	0.48	0.31	0.46	0.13
Years of Education	13.31	2.46	12.73	2.41	0.24
N(Observation)	53,982		12,689		

Notes: The table shows summary statistics and normalized differences for socio-demographic characteristics for treated and non-treated commuters before the implementation of the congestion charge in 2005. Treated commuters are defined as individuals who cross the congestion zone to or from Stockholm on their way to work. Non-treated commuters are defined as individuals who reside and work outside the congestion zone and pass the Essinge bypass or the Lidingö route on the (time-minimizing) route between home and work. The normalized difference expresses the raw difference in means between groups scaled by the square root of the average within-group variance (Imbens and Rubin 2015; Austin 2009; Baker et al. 2025).

C. Sample selection and treatment definitions

C.1. Definition of control and treatment group

The potential pool of *treated commuters* are individuals who crossed the congestion zone to or from Stockholm on their way to work in 2006. This includes all individuals who reside within the congestion zone and work outside, plus those who live outside the area and work inside.

The potential pool of *non-treated commuters* are individuals who live and work outside the congestion zone and use the Essinge bypass or the Lidingö route on their (time-minimizing) way to and from work. We exclude individuals who live and work outside the congestion zone from the non-treated commuters if their (time-minimizing) route went through the city center as these individuals faced congestion charges on their commute. Finally, we exclude individuals living and working within the congestion zone because they are less likely to be affected by the congestion charges.

The allocation of individuals into treated commuters and non-treated commuters is based on toll payments in 2005. This control and treatment group classification results in 335,723 treated and 80,522 non-treated commuters. 41,121 treated commuters reside inside and work outside, while 294,602 live outside and commute into the congestion zone. Table C1 summarizes the classification of treated and non-treated commuters depending on the neighborhood and workplace location.

Table C1: Treatment and control group

		Workplace Location	
		Inside	Outside
Neighborhood Location	Inside	Excluded	<i>Treated commuters</i>
	Outside	<i>Treated commuters</i>	<i>Non-treated commuters</i> via Essinge/Lidingö

C.2. Sample selection

The administrative data sources provided by Statistics Sweden contain information at the individual-level for all individuals 18 years or older. We further restrict our sample in the following ways:

1. Individuals must have existed in the dataset in 2006.
2. Individuals must be employed.
3. Individuals must fall within the definitions of *treated commuters* or *non-treated commuters*.
 - We remove people who both work and live inside of Stockholm’s congestion zone
 - We remove individuals working and living outside of Stockholm’s congestion zone who do not cross the cordon zone.
4. Individuals must have a commuting distance between 3 and 50 kilometers.
5. Individuals must be observed after the congestion charge was implemented.
6. Individuals must own at least one but not more than three vehicles.

As treatment is defined as a time-invariant attribute on the individual-level, the individual must have existed in 2006 to be part of the analysis. Individuals must be employed and own at least one vehicle to ensure that the person likely commutes to a workplace. We exclude individuals with more than three vehicles to ensure these are not used for business purposes. We consider work distances below 3 kilometers to be walking or cycling distances, which are less likely to be affected by congestion charges. The 50-kilometers cutoff ensures comparable work distances for treated and non-treated commuters. Finally, individuals need to fall within the definitions of our treatment and be observed after the implementation of the congestion charge.²² We do not require individuals to be observed during all years to be included in our sample (2003-2008), meaning that the dataset is an unbalanced panel.

Applying the sample restrictions listed above leaves us with a dataset of 97,298 unique individuals over six years, resulting in 416,245 annual observations. Table C2 shows how each sample selection criterion affects the number of observations. Restricting the sample to individuals observed in all years significantly reduces the number of observations (column 7). However, results based on a balanced sample are similar to our main results (Table D6). Finally, note that when estimating the effect on commuting distance, we restrict the sample to consider only individuals outside the congestion zone; this sample is summarized in column 8 of Table C2.

22. As we cannot identify the work-trip exposure of company cars, we exclude those cars throughout the entire empirical analysis.

Table C2: Observations by year and sample selection criteria

	Sample selection criteria					Main sample	Balanced Sample	Outside zone
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
<i>Years</i>								
2003	1,217,085	845,890	298,372	280,328	125,872	53,176	38,762	48,185
2004	1,236,578	859,827	301,486	283,134	139,182	59,138	38,762	53,485
2005	1,260,738	870,769	306,109	287,582	157,940	66,671	38,762	50,434
2006	1,293,780	903,686	315,005	295,839	192,485	77,653	38,762	50,199
2007	1,329,834	972,133	336,640	315,534	192,485	79,259	38,762	48,771
2008	1,366,838	993,526	345,715	324,067	192,485	80,348	38,762	47,578
Individuals	1,525,337	1,247,558	605,322	570,621	192,485	97,298	38,762	57,905
Total	7,704,853	5,445,831	1,903,327	1,786,384	1,000,449	416,245	232,572	298,652

Notes: This table shows how observations per year are reduced as various sample selection criteria are imposed: (1) all individuals in Stockholm existed in 2006; (2) removing unemployed individuals; (3) removing individuals that do not fall within the definitions of treated or non-treated commuters; (4) removing individuals with a commuting distance of less than 3km and more than 50km; (5) removing individuals who were not observed between 2006 and 2008; (6) removing individuals without vehicles or more than three vehicles. Column (6) is our main sample. Column (7) corresponds to the balanced sample. Column (8) removes individuals that reside within the congestion zone prior to the congestion trial.

C.3. The congestion rebound effect

The DiD estimator that we use in our main specifications can be written as follows, where an individual's driving choices depend on treatment status, T_i , as well as the treatment status of others, T_{-i} :

$$\hat{\beta} = [\bar{y}^{post}(T_i = 1|T_{-i}) - \bar{y}^{pre}(T_i = 1)] - [\bar{y}^{post}(T_i = 0|T_{-i}) - \bar{y}^{pre}(T_i = 0)].$$

To separate the change in traffic conditions from the direct price effect of the policy, we can decompose the outcome for both treated and non-treated commuters:

$$\begin{aligned} \hat{\beta} = & \underbrace{[\bar{y}^{post}(T_i = 1|T_{-i} = 0)]}_{\text{price effect treated}} + \underbrace{[\Delta \bar{y}_{traffic}^{post}(T_i = 1|T_{-i} = 1) - \bar{y}^{pre}(T_i = 1)]}_{\text{traffic effect treated}} \\ & - \underbrace{[\bar{y}^{post}(T_i = 0|T_{-i} = 0)]}_{\text{price effect non-treated}} + \underbrace{[\Delta \bar{y}_{traffic}^{post}(T_i = 0|T_{-i} = 1) - \bar{y}^{pre}(T_i = 0)]}_{\text{traffic effect non-treated}}. \end{aligned}$$

As treated and non-treated commuters share the same home-work route when entering the congestion zone, both commuter groups experience a similar change in travel conditions:

$$\hat{\beta} = [\bar{y}^{post}(T_i = 1|T_{-i} = 0) - \bar{y}^{pre}(T_i = 1)] - [\bar{y}^{post}(T_i = 0|T_{-i} = 0) - \bar{y}^{pre}(T_i = 0)]. \quad (C1)$$

Hence, our estimated coefficients reflect responses to Stockholm's congestion charge but not the "rebound" effect from lighter traffic.

D. Supporting results and robustness checks

D.1. Additional tables

Table D1: The impact of congestion pricing on vehicle kilometers traveled: imposition versus removal

	Vehicle Kilometers Traveled		
	(1) Alternative	(2) Fossil	(3) Total
A. Alternative Fuel Exemption			
Post x Treated Commuters	103.2*** (22.7)	-256.7*** (71.0)	-153.5** (69.5)
Mean Vehicle Kilometers (2005)	96.5	15,202.4	15,299
B. Removal of Alternative Exemption			
Post x Treated Commuters	-93.3* (48.2)	211.8*** (81.0)	118.6 (76.2)
Mean Vehicle Kilometers (2012)	1,885.1	12,168.5	14,053.6

Notes: This table displays the coefficients from a DiD specification (equation 7) that estimates the impact of Stockholm's congestion pricing policy on vehicle kilometers traveled. Each column uses a different dependent variable. The dependent variable in column 1 is the annual kilometers traveled in alternative fuel vehicles. Columns 2 and 3 have analogous dependent variables for fossil fuel vehicles and all vehicles, respectively. We estimate responses in kilometers traveled for two policy changes. Panel A shows estimates from the DiD using the introduction of the congestion pricing policy, which included exemptions for alternative fuel vehicles. Panel B shows estimates from the DiD using the removal of the alternative fuel exemption in 2012. For Panel A, the sample is restricted to 2003-2008, where 2006-2008 is the post-period. The vehicle kilometers traveled for each type of car are reported below the coefficients. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D2: The impact of congestion pricing on home and workplace locations

	Probability of Moving		
	(1) Anywhere	(2) Outside	(3) Congestion
A. Residential Move			
Post x Treated Commuters	-0.005*** (0.002)	-0.006*** (0.002)	0.002*** (0.000)
Mean Dep. Variable (2005)	0.066	0.066	0
B. Workplace Relocation			
Post x Treated Commuters	0.006*** (0.002)	0.010*** (0.001)	-0.004*** (0.002)
Mean Dep. Variable (2005)	0.095	0.021	0.074
New Employer	-0.006*** (0.002)	0.003** (0.001)	-0.009*** (0.001)
Old Employer	0.012*** (0.001)	0.007*** (0.001)	0.005*** (0.001)

Notes: This table displays the coefficients from a DiD specification (equation 7) that estimates the impact of Stockholm's congestion pricing policy on where individuals live and work. The first column displays estimates of the change in the probability of any move; the second column uses a dependent variable that equals one if an individual moves to a location outside the cordon zone; the third column uses a dependent variable that equals one if an individual moves into the cordon zone. Panel A displays results where the dependent variable is an individual's home location; panel B displays results where the dependent variable is an individual's workplace location, and further subsets results into workplace moves where the individual changed firms (the penultimate row) versus workplace moves where the individual stayed at the same firm (the final row). Control group means from the last pre-period year are reported below each coefficient. The sample is restricted to 2003-2008, where 2006-2008 is the post-period. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D3: The heterogeneous effects of congestion pricing on commuting distances

	Commuting Distance			
	(1)	(2)	(3)	(4)
Panel A. Income				
Post x Paying Commuters	-0.0491 (0.0455)	-0.0233 (0.0357)	-0.0383 (0.0341)	-0.0662* (0.0338)
Panel B. Family Status				
Post x Paying Commuters	-0.0942** (0.0452)	-0.0233 (0.0357)	-0.0383 (0.0341)	-0.0662* (0.0338)
Panel C. Education				
Post x Paying Commuters	-0.0381 (0.0348)	-0.0568* (0.0327)	-0.0049 (0.0321)	-0.0837* (0.0472)
Panel D. Age				
Post x Paying Commuters	0.0169 (0.0573)	-0.0662** (0.0328)	-0.0544* (0.0291)	0.0598* (0.0354)
Panel E. Commute Distance				
Post x Paying Commuters	-0.1095** (0.0477)	0.0284 (0.0358)	0.0311 (0.0350)	-0.2090*** (0.0387)

Notes: This table displays the results from the DiD specification (equation 7) that estimates the impact of Stockholm's congestion pricing policy on commuting distances. We break down these estimates by five socio-economic characteristics: Income (Panel A), family status (Panel B), education (Panel C), age (Panel D), and commuting distance (Panel E). Columns refer to individuals with an annual income of (1) less than 200,000 SEK, (2) between 200,000 and 400,000 SEK, (3) between 400,000 and 600,000 SEK, and (4) more than 600,000 SEK in Panel (A); (1) singles without children, (2) singles with children, (3) couples without children, and (4) couples with children in Panel (B); individuals with an educational level of (1) pre-high school, (2) high school, (3) bachelor's degree, and (4) master's degree in Panel (C); individuals aged (1) below 35, (2) between 35 and 45, (3) between 45 and 60, and (4) above 60 in Panel (D); and individuals with a commuting distance of (1) less than 10 kilometers, (2) between 10 and 15 kilometers, (3) between 15 and 25 kilometers, and (4) more than 25 kilometers in Panel (E). The sample is restricted to 2003-2008, where 2006-2008 is the post-period. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D4: Estimates for different treatment timing

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A. Vehicle Ownership			
Post x Treated Commuters	0.0064*** (0.0014)	-0.0078** (0.0034)	-0.0014 (0.0031)
Mean Car Ownership (t-1)	0.014	1.131	1.145
B. Vehicle Kilometers			
Post x Treated Commuters	103.2*** (22.7)	-256.7*** (71.0)	-153.5** (69.5)
Mean Kilometers Traveled (t-1)	96.5	15,202.4	15,299
C. Commuting Distance			
Post x Treated Commuters			-0.070** (0.033)
Mean Commute Distance (t-1)			17.5

Notes: This table displays the coefficients from a DiD specification (equation 7) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), vehicle kilometers traveled (Panel B), and commuting distance (Panel C), using the different post period specification for short- and long-run outcomes. The dependent variables in Panel A are indicators for whether an individual owns an alternative fuel vehicle (column 1), a fossil fuel vehicle (column 2), or any vehicle (column 3). The dependent variables in Panel B are vehicle kilometers traveled in alternative fuel vehicles (column 1), fossil fuel vehicles (column 2), and all vehicles (column 3). The dependent variable in Panel C is the home-to-work commuting distance (column 3). Control group means from the last pre-period year are reported below each coefficient. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for vehicle ownership and commuting distances, and 2006-2008 is the post-period for vehicle kilometers. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D5: Across-city Differences-in-Differences

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A. Vehicle Ownership			
Post x Treated Commuters	0.0047*** (0.0009)	-0.0126*** (0.0027)	-0.0079*** (0.0025)
Mean Car Ownership Control (2005)	0.007	1.168	1.175
B. Vehicle Kilometers			
Post x Treated Commuters	98.3*** (18.1)	-424.1*** (55.7)	-326.0*** (54.7)
Mean Kilometers Traveled Control (2005)	225.7	16,294.5	16,426.5
	Moving Outcome		
	(1) Residential	(2) Workplace	(3) Distance
C. Commuting Decision			
Post x Stockholm Commuters	0.003* (0.001)	0.014*** (0.002)	-0.015 (0.010)
Mean Commute Control (2005)	0.05	0.05	16.3

Notes: This table displays the coefficients from the across-city DiD specification that estimates the impact of Stockholm's congestion pricing policy relative to commuters in Malmö and Gothenburg, on vehicle ownership (Panel A), vehicle kilometers traveled (Panel B), and commuting decisions (Panel C). We restrict the sample to commuters who reside outside the city center but work within the city center. The dependent variables in Panel A are indicators for whether an individual owns an alternative fuel vehicle (column 1), a fossil fuel vehicle (column 2), or any vehicle (column 3). The dependent variables in Panel B are vehicle kilometers traveled in alternative fuel vehicles (column 1), fossil fuel vehicles (column 2), and all vehicles (column 3). Panel C displays estimates of changes in residential moves (column 1), workplace relocations (column 2), and the home-to-work commuting distance (column 3). Control group means from the last pre-period year are reported below each coefficient. The sample is restricted to 2003-2008, where 2006-2008 is the post-period. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D6: Estimates using a balanced panel

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A. Vehicle Ownership			
Post x Treated Commuters	0.0042*** (0.0016)	-0.0059 (0.0048)	-0.0017 (0.0046)
Mean Car Ownership (2005)	0.007	1.164	1.171
B. Vehicle Kilometers			
Post x Treated Commuters	73.9** (31.7)	-270.6*** (90.8)	-196.6** (87.9)
Mean Kilometers Traveled (2005)	102.9	15,695.6	15,798.5
C. Commuting Distance			
Post x Treated Commuters			-0.108*** (0.037)
Mean Commute Distance (2005)			17.5

Notes: This table displays the coefficients from a DiD specification (equation 7) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), vehicle kilometers traveled (Panel B), and commuting distance (Panel C), using the balanced sample from column (7) in Table C2. The dependent variables in Panel A are indicators for whether an individual owns an alternative fuel vehicle (column 1), a fossil fuel vehicle (column 2), or any vehicle (column 3). The dependent variables in Panel B are vehicle kilometers traveled in alternative fuel vehicles (column 1), fossil fuel vehicles (column 2), and all vehicles (column 3). The dependent variable in Panel C is the home-to-work commuting distance (column 3). Control group means from the last pre-period year are reported below each coefficient. The sample is restricted to 2003-2008, where 2006-2008 is the post-period. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D7: Treatment effects for individuals living outside of the congestion zone

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A. Vehicle Ownership			
Post x Treated Commuters	0.0030*** (0.0011)	-0.0058* (0.0035)	-0.0028 (0.0033)
Mean Car Ownership (2005)	0.007	1.138	1.145
B. Vehicle Kilometers			
Post x Treated Commuters	63.8*** (22.0)	-234.7*** (71.4)	-170.8** (69.9)
Mean Kilometers Traveled (2005)	96.5	15,202.4	15,299
C. Commuting Distance			
Post x Treated Commuters			-0.106*** (0.035)
Mean Commute Distance (2005)			17.5

Notes: This table displays the coefficients from a DiD specification (equation 7) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), vehicle kilometers traveled (Panel B), and commuting distance (Panel C), restricting the sample of treated commuters to individuals who live outside of the congestion zone. The dependent variables in Panel A are indicators for whether an individual owns an alternative fuel vehicle (column 1), a fossil fuel vehicle (column 2), or any vehicle (column 3). The dependent variables in Panel B are vehicle kilometers traveled in alternative fuel vehicles (column 1), fossil fuel vehicles (column 2), and all vehicles (column 3). The dependent variable in Panel C is the home-to-work commuting distance (column 3). Control group means from the last pre-period year are reported below each coefficient. The sample is restricted to 2003-2008, where 2006-2008 is the post-period. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D8: Treatment effects for individuals living inside the congestion zone

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A. Vehicle Ownership			
Post x Treated Commuters	0.0144*** (0.0014)	-0.0185*** (0.0036)	-0.0041 (0.0033)
Mean Car Ownership (2005)	0.007	1.138	1.145
B. Vehicle Kilometers			
Post x Treated Commuters	266.6*** (28.2)	-313.2*** (77.0)	-47.1 (74.6)
Mean Kilometers Traveled (2005)	96.5	15,202.4	15,299
C. Commuting Distance			
Post x Treated Commuters			-0.108*** (0.037)
Mean Commute Distance (2005)			17.5

Notes: This table displays the coefficients from a DiD specification (equation 7) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), vehicle kilometers traveled (Panel B), and commuting distance (Panel C), restricting the sample of treated commuters to individuals who live inside the congestion zone. The dependent variables in Panel A are indicators for whether an individual owns an alternative fuel vehicle (column 1), a fossil fuel vehicle (column 2), or any vehicle (column 3). The dependent variables in Panel B are vehicle kilometers traveled in alternative fuel vehicles (column 1), fossil fuel vehicles (column 2), and all vehicles (column 3). The dependent variable in Panel C is the home-to-work commuting distance (column 3). Control group means from the last pre-period year are reported below each coefficient. The sample is restricted to 2003-2008, where 2006-2008 is the post-period. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D9: Effects including inside-inside commuters

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A. Vehicle Ownership			
Post x Treated Commuters	0.0069*** (0.0012)	-0.0115*** (0.0035)	-0.0045 (0.0033)
Mean Car Ownership (2005)	0.007	1.132	1.139
B. Vehicle Kilometers			
Post x Treated Commuters	135.6*** (23.2)	-288.4*** (70.3)	-152.7** (68.6)
Mean Kilometers Traveled (2005)	98.5	14,990.8	15,089.4
C. Commuting Distance			
Post x Treated Commuters			-0.110*** (0.035)
Mean Commute Distance (2005)			17.5

Notes: This table displays the coefficients from a DiD specification (equation 7) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), vehicle kilometers traveled (Panel B), and commuting distance (Panel C), extending the sample of treated commuters to individuals who both live and work inside the congestion zone. The dependent variables in Panel A are indicators for whether an individual owns an alternative fuel vehicle (column 1), a fossil fuel vehicle (column 2), or any vehicle (column 3). The dependent variables in Panel B are vehicle kilometers traveled in alternative fuel vehicles (column 1), fossil fuel vehicles (column 2), and all vehicles (column 3). The dependent variable in Panel C is the home-to-work commuting distance (column 3). Control group means from the last pre-period year are reported below each coefficient. The sample is restricted to 2003-2008, where 2006-2008 is the post-period. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D10: Estimates with workplaces near congestion zone

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A. Vehicle Ownership			
Post x Treated Commuters	0.0032** (0.0014)	-0.0112** (0.0045)	-0.0080* (0.0043)
Mean Car Ownership (2005)		1.139	1.146
B. Vehicle Kilometers			
Post x Treated Commuters	67.2** (27.3)	-294.4*** (90.3)	-227.0** (88.6)
Mean Kilometers Traveled (t-1)	92.7	15,117.9	15,210.7
C. Commuting Distance			
Post x Treated Commuters			-0.117*** (0.043)
Mean Commute Distance (2005)			17.5

Notes: This table displays the coefficients from a DiD specification (equation 7) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), vehicle kilometers traveled (Panel B), and commuting distance (Panel C), restricting the sample of treated commuters to individuals with workplaces that are within three kilometers of the congestion zone. The dependent variables in Panel A are indicators for whether an individual owns an alternative fuel vehicle (column 1), a fossil fuel vehicle (column 2), or any vehicle (column 3). The dependent variables in Panel B are vehicle kilometers traveled in alternative fuel vehicles (column 1), fossil fuel vehicles (column 2), and all vehicles (column 3). The dependent variable in Panel C is the home-to-work commuting distance (column 3). Control group means from the last pre-period year are reported below each coefficient. The sample is restricted to 2003-2008, where 2006-2008 is the post-period. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D11: Estimates with workplace-location fixed effects

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A. Vehicle Ownership			
Post x Treated Commuters	0.0058*** (0.0011)	-0.0062* (0.0035)	-0.0004 (0.0034)
Mean Car Ownership (2005)	0.007	1.138	1.145
B. Vehicle Kilometers			
Post x Treated Commuters	111.9*** (22.9)	-227.7*** (72.6)	-115.8 (71.3)
Mean Kilometers Traveled (2005)	96.5	15,202.4	15,299
C. Commuting Distance			
Post x Treated Commuters			-0.116*** (0.035)
Mean Commute Distance (2005)			17.5

Notes: This table displays the coefficients from a DiD specification (equation 7) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), vehicle kilometers traveled (Panel B), and commuting distance (Panel C), including workplace-location fixed effects. The dependent variables in Panel A are indicators for whether an individual owns an alternative fuel vehicle (column 1), a fossil fuel vehicle (column 2), or any vehicle (column 3). The dependent variables in Panel B are vehicle kilometers traveled in alternative fuel vehicles (column 1), fossil fuel vehicles (column 2), and all vehicles (column 3). The dependent variable in Panel C is the home-to-work commuting distance (column 3). Control group means from the last pre-period year are reported below each coefficient. The sample is restricted to 2003-2008, where 2006-2008 is the post-period. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D12: Estimates for low-income groups

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A. Vehicle Ownership			
Post x Treated Commuters	-0.0006 (0.0014)	0.0081* (0.0043)	0.0075* (0.0040)
Mean Car Ownership (2005)	0.005	1.112	1.117
B. Vehicle Kilometers			
Post x Treated Commuters	-13.2 (29.2)	-244.2*** (88.7)	-257.5*** (88.1)
Mean Kilometers Traveled (2005)	79.5	14,130.4	14,209.9
C. Commuting Distance			
Post x Treated Commuters			-0.155*** (0.044)
Mean Commute Distance (2005)			18

Notes: This table displays the coefficients from a DiD specification (equation 7) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), vehicle kilometers traveled (Panel B), and commuting distance (Panel C), for individuals with an annual income of less than 300,000 SEK. The dependent variables in Panel A are indicators for whether an individual owns an alternative fuel vehicle (column 1), a fossil fuel vehicle (column 2), or any vehicle (column 3). The dependent variables in Panel B are vehicle kilometers traveled in alternative fuel vehicles (column 1), fossil fuel vehicles (column 2), and all vehicles (column 3). The dependent variable in Panel C is the home-to-work commuting distance (column 3). Control group means from the last pre-period year are reported below each coefficient. The sample is restricted to 2003-2008, where 2006-2008 is the post-period. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D13: Estimates for medium-income groups

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A. Vehicle Ownership			
Post x Treated Commuters	0.0053*** (0.0012)	-0.0144*** (0.0037)	-0.0091*** (0.0035)
Mean Car Ownership (2005)	0.008	1.122	1.13
B. Vehicle Kilometers			
Post x Treated Commuters	93.2*** (24.1)	-420.1*** (74.3)	-326.8*** (72.5)
Mean Kilometers Traveled (2005)	110.7	14,950.4	15,061.2
C. Commuting Distance			
Post x Treated Commuters			-0.133*** (0.037)
Mean Commute Distance (2005)			18.2

Notes: This table displays the coefficients from a DiD specification (equation 7) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), vehicle kilometers traveled (Panel B), and commuting distance (Panel C), for individuals with an annual income of between 300,000 to 600,000 SEK. The dependent variables in Panel A are indicators for whether an individual owns an alternative fuel vehicle (column 1), a fossil fuel vehicle (column 2), or any vehicle (column 3). The dependent variables in Panel B are vehicle kilometers traveled in alternative fuel vehicles (column 1), fossil fuel vehicles (column 2), and all vehicles (column 3). The dependent variable in Panel C is the home-to-work commuting distance (column 3). Control group means from the last pre-period year are reported below each coefficient. The sample is restricted to 2003-2008, where 2006-2008 is the post-period. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D14: Estimates for high-income groups

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A. Vehicle Ownership			
Post x Treated Commuters	0.0103*** (0.0017)	-0.0097** (0.0045)	0.0007 (0.0042)
Mean Car Ownership (2005)	0.017	1.205	1.212
B. Vehicle Kilometers			
Post x Treated Commuters	227.8*** (33.5)	93.9 (87.8)	321.7*** (85.6)
Mean Kilometers Traveled (2005)	77.8	16,912.5	16,990.4
C. Commuting Distance			
Post x Treated Commuters			-0.053 (0.041)
Mean Commute Distance (2005)			17.4

Notes: This table displays the coefficients from a DiD specification (equation 7) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), vehicle kilometers traveled (Panel B), and commuting distance (Panel C), for individuals with an annual income of over 600,000 SEK. The dependent variables in Panel A are indicators for whether an individual owns an alternative fuel vehicle (column 1), a fossil fuel vehicle (column 2), or any vehicle (column 3). The dependent variables in Panel B are vehicle kilometers traveled in alternative fuel vehicles (column 1), fossil fuel vehicles (column 2), and all vehicles (column 3). The dependent variable in Panel C is the home-to-work commuting distance (column 3). Control group means from the last pre-period year are reported below each coefficient. The sample is restricted to 2003-2008, where 2006-2008 is the post-period. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D15: Congestion prices under varying assumptions about the share of cordon trips

	Green trips		Brown trips		Optimal charge
Share of congestion trips	Inside	Outside	Inside	Outside	
32%	1.8	3.4	278.0	544.1	€10.02
34%	1.9	3.3	295.8	528.1	€10.03
36%	2.0	3.2	312.7	512.1	€10.04
38%	2.1	3.1	330.1	496.1	€10.06
40%	2.2	3.0	347.8	480.1	€10.07
42%	2.3	2.9	364.8	464.1	€10.08
44%	2.4	2.8	382.2	448.1	€10.08
46% (Baseline)	2.5	2.7	399.6	432.1	€10.09
48%	2.6	2.6	416.9	416.1	€10.10
50%	2.8	2.5	434.3	400.1	€10.11
52%	2.9	2.4	451.7	384.1	€10.12
54%	3.0	2.3	469.0	368.1	€10.13
56%	3.1	2.2	486.4	352.1	€10.14
58%	3.2	2.1	503.8	336.1	€10.15
60%	3.3	2.0	521.2	320.1	€10.16

Notes: This table reports the number of green and brown vehicle trips occurring inside and outside the congestion zone, along with the corresponding optimal congestion charge, under varying assumptions about what share of total VKT constitutes trips that use the congestion zone. Our baseline results using a 46% share from the 2007 National Travel Survey are shown in bold.

D.2. Additional figures

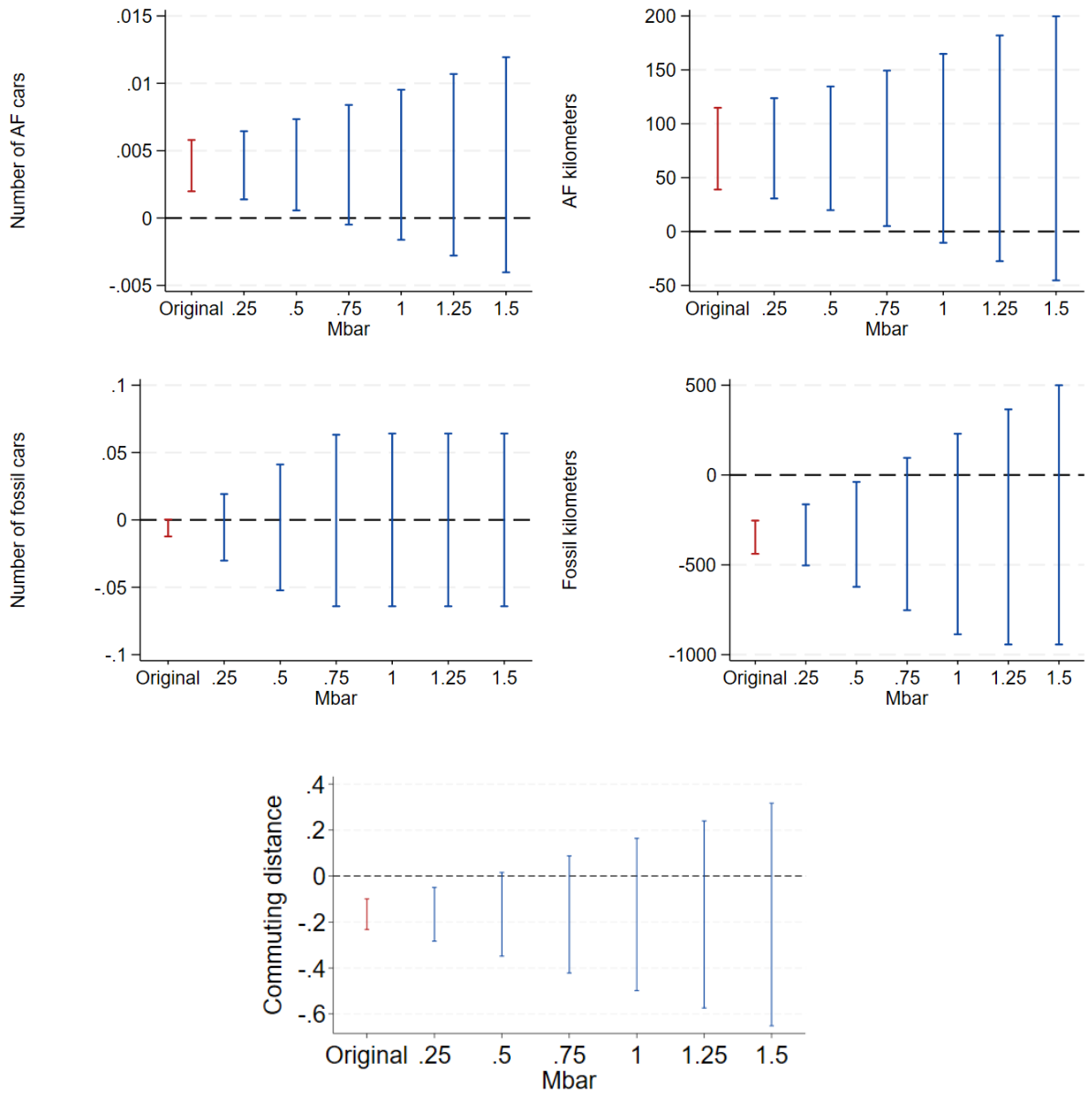


Figure D1: Parallel trends sensitivity analysis

Notes: This figure displays the bounds on the relative magnitudes of violations of parallel trends for the average post-treatment period for alternative fuel vehicle ownership and usage (Panel A), fossil fuel vehicle ownership and usage (Panel B), and commuting distance (Panel C). The 95% confidence intervals for the original estimated post-period treatment effect (in red) are compared to those allowing for violations of the post-treatment parallel trends assumption, relative to the estimated pre-treatment coefficients, up to a parameter M (in blue).

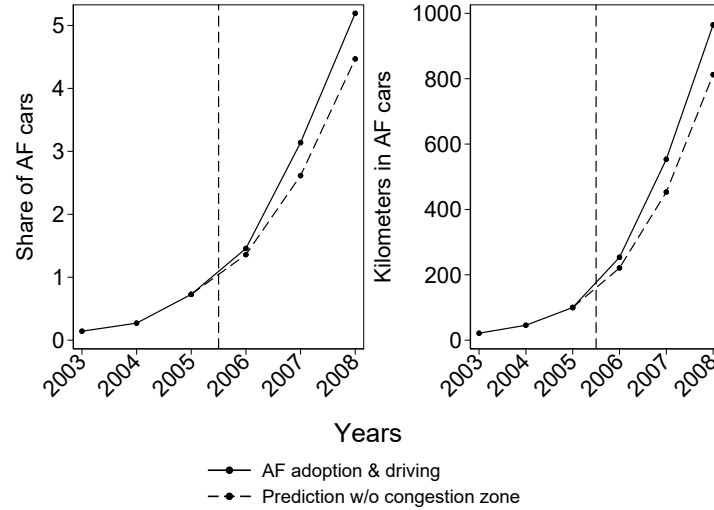


Figure D2: Predicted vehicle ownership and driving behavior

Notes: The solid lines in Panel A and Panel B show the share of individuals among treated commuters in Stockholm who owned an alternative fuel vehicle and the kilometers traveled in alternative fuel vehicles from 2003-2008. The dashed lines in Panel A and B show the predicted share of individuals among treated commuters in Stockholm who would have owned an alternative fuel vehicle and the predicted alternative fuel vehicle kilometers traveled in the absence of the congestion charge, based on the treatment estimates reported in Figure 5. The vertical dashed line denotes the imposition of the Stockholm Congestion Trial (2006).

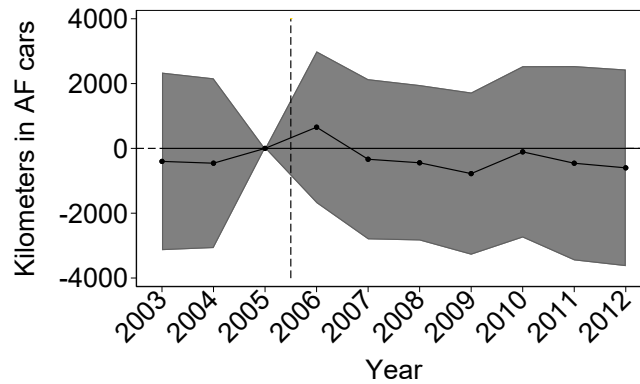
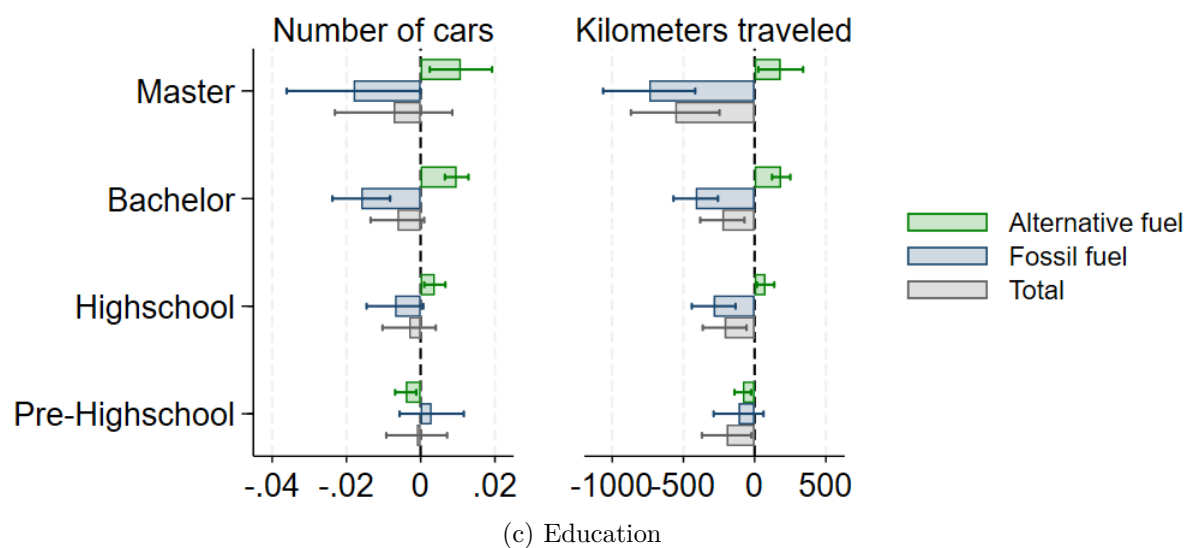
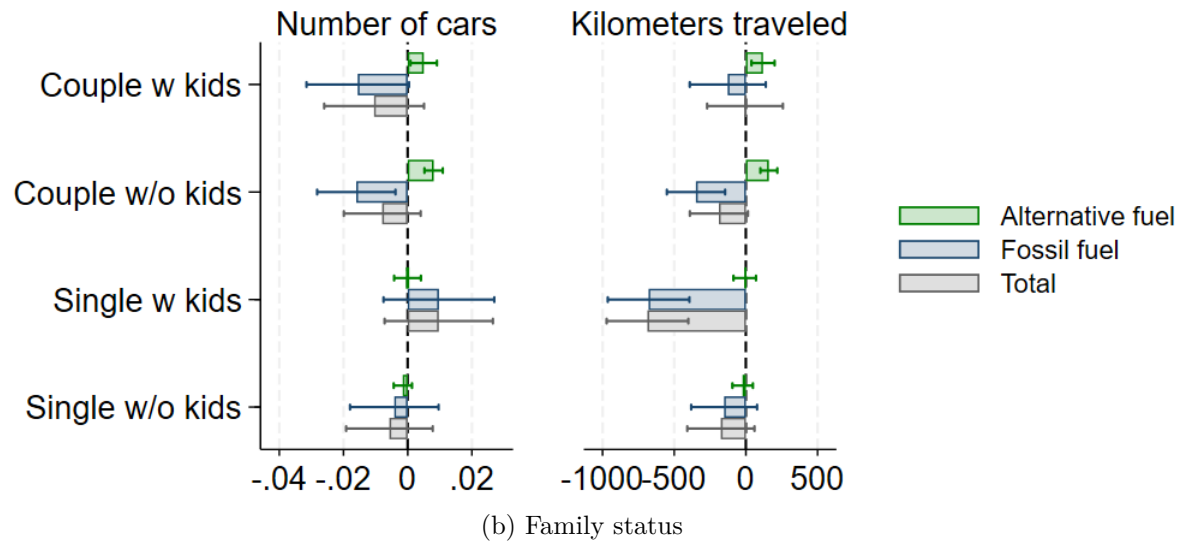
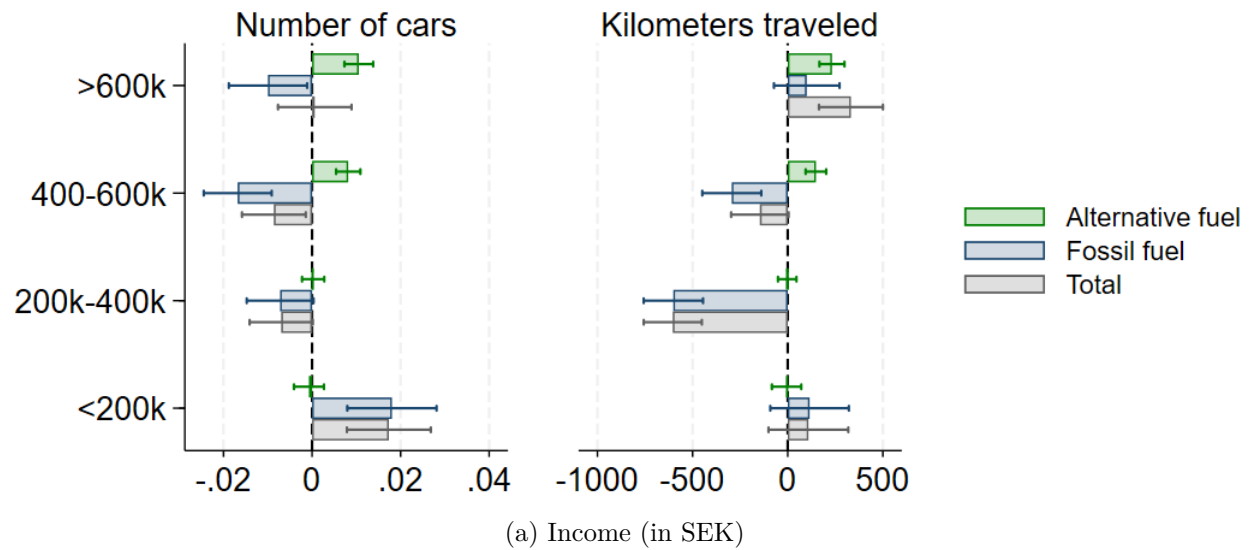


Figure D3: The impact on VKT among drivers who already owned exactly one green car

Notes: This figure plots the annual treatment effect on vehicle kilometers traveled in alternative fuel cars among drivers who already owned exactly one green car and no other vehicles prior to the introduction of the congestion charge using the dynamic DiD specification (equation 8), where β_{2005} is normalized to zero. Since these drivers were exempt from charges but still affected by changes in overall traffic conditions, the change in alternative fuel kilometers on the y-axis captures the rebound effect. Treated and non-treated commuters are those who cross the congestion zone between their home and workplace (i.e., reduced congestion) and those who live and work outside the congestion zone (i.e., no congestion changes), conditional on owning a green car prior to the zone's implementation. Standard errors are clustered at the neighborhood level.



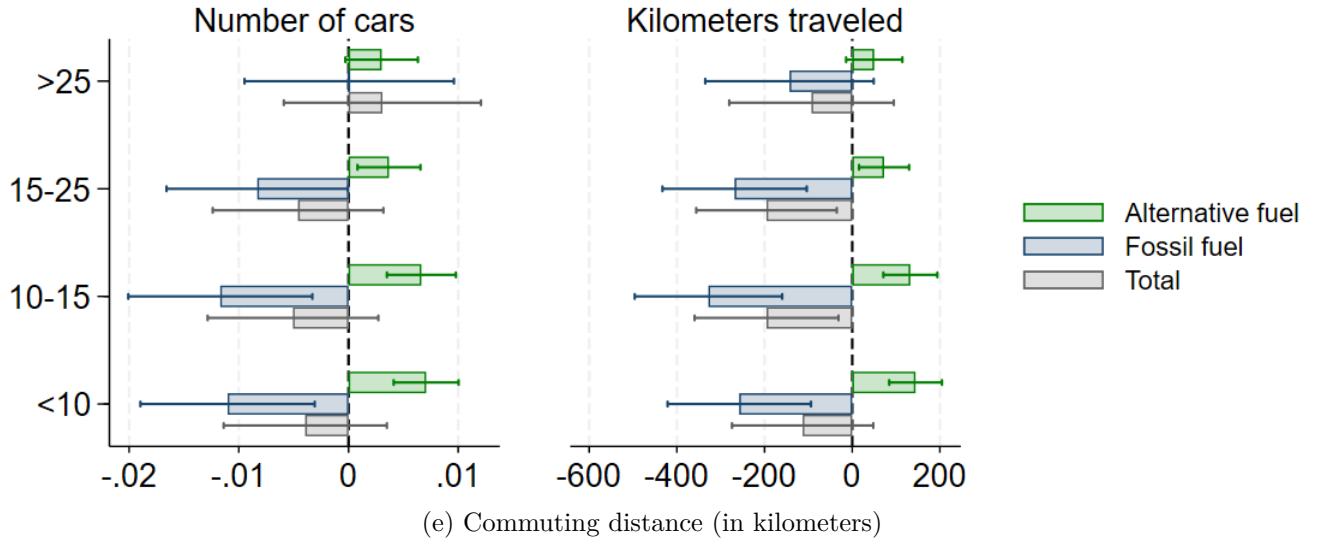
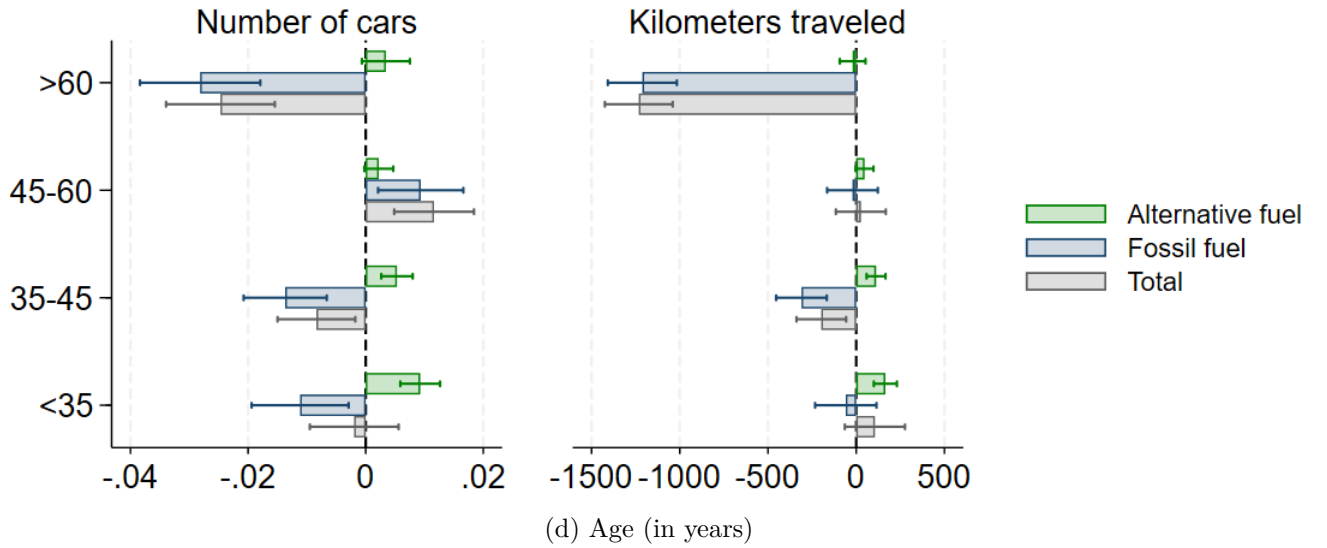


Figure D4: The impact of congestion pricing by socio-economic group

Notes: These figures plot the coefficients β_k on vehicle ownership and driving behavior for alternative (green), fossil fuel (blue), and any vehicle (gray) for five socio-economic characteristics: income (Panel A), family status (Panel B), education (Panel C), age (Panel D), and commuting distance (Panel E). Green indicates alternative fuel vehicles, blue indicates fossil fuel vehicles, and gray indicates all vehicles. The dependent variable for vehicle ownership is a dummy variable equal to 1 if the individual owns the type of vehicle and 0 otherwise. The dependent variable for driving behavior indicates the vehicle kilometers traveled with the type of vehicle. Groups are based on 2006 demographics. 95%-confidence intervals are indicated through whiskers and reflect robust standard errors clustered by neighborhoods.

D.3. Distributional burden of Stockholm's congestion pricing

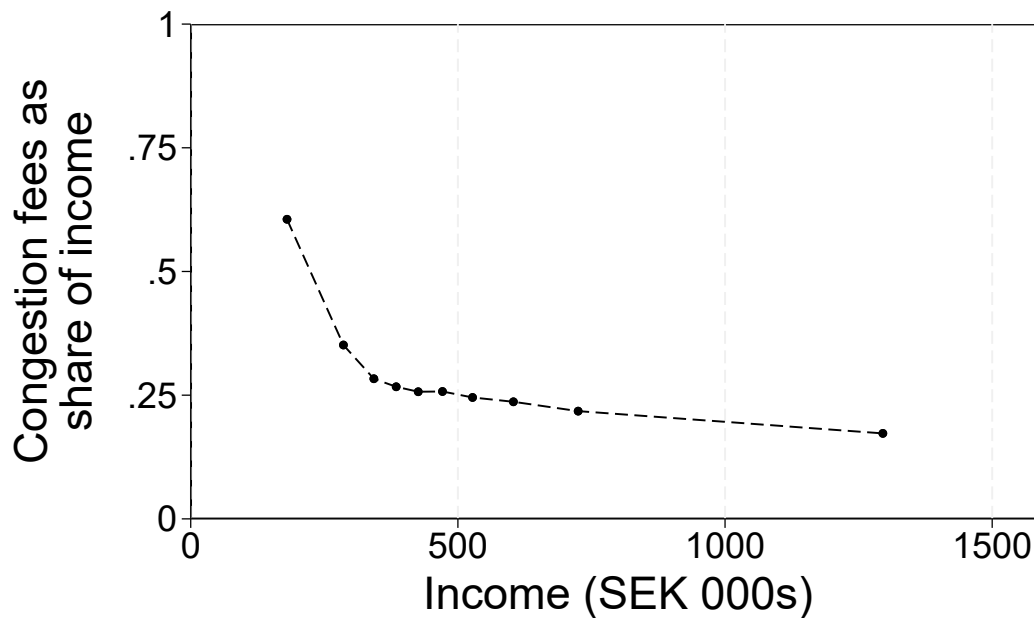


Figure D5: Congestion charges by share of salary

Notes: This figure plots Stockholm's congestion charges as a share of income for each income decile in 2016. We use data from the vehicle registry provided by Statistics Sweden, which includes records of annual congestion charges (*trängselskatt*) per individual.

E. Details of calculating the optimal congestion charge

We combine our empirical results with equation (4) to recover estimates of the optimal congestion charge in the presence of green vehicle exemptions.

E.1. Converting changes in vehicle kilometers traveled to changes in trips

We observe individual-level data on vehicle kilometers traveled, but not on cordon zone trips. As such, we convert changes in vehicle kilometers traveled to changes in trips using survey data from Stockholm. To begin, we write the total kilometers traveled for each vehicle type as the sum of kilometers traveled on cordon trips and the sum of kilometers traveled on outside trips:

$$KM_g = v^c \cdot t_g^c + v^o \cdot t_g^o \quad (E1)$$

$$KM_b = v^c \cdot t_b^c + v^o \cdot t_b^o \quad (E2)$$

We observe the individual-level vehicle kilometers traveled for both fuel types (Panel A of Table D1) and assume that the average distance of a congestion zone trip (v^c) equals the driving distance between a person's neighborhood and workplace. To get an estimate of the number of congestion and non-congestion zone trips (t^c , t^o), we use the fact that 46% of kilometer-weighted trips are business-related (The Swedish National Travel Survey, 2007). We then calculate the total number of trips in the congestion zone for green and brown vehicles as follows:

$$\begin{aligned} 0.46 \cdot KM_g &= v^c \cdot t_g^c \\ t_g^c &= \frac{0.46 \cdot KM_g}{v^c} = \frac{0.46 \cdot 96.5km}{17.5km} \approx 2.5 \end{aligned} \quad (E3)$$

$$\begin{aligned} 0.46 \cdot KM_b &= v^c \cdot t_b^c \\ t_b^c &= \frac{0.46 \cdot KM_b}{v^c} = \frac{0.46 \cdot 15,202.4km}{17.5km} \approx 399.6 \end{aligned} \quad (E4)$$

We assume that the average distance traveled for a non-congestion zone trip (v^o) equals the average reported trip length in the 2007 Swedish National Travel Survey. We then obtain the number of non-congestion zone trips for green and brown vehicles as follows:

$$\begin{aligned}
0.54 \cdot KM_g &= v^o \cdot t_g^o \\
t_g^o &= \frac{0.54 \cdot KM_g}{v^o} = \frac{0.54 \cdot 96.5km}{19km} \approx 2.7
\end{aligned} \tag{E5}$$

$$\begin{aligned}
0.54 \cdot KM_b &= v^o \cdot t_b^o \\
t_b^o &= \frac{0.54 \cdot KM_b}{v^o} = \frac{0.54 \cdot 15,202.4km}{19km} \approx 432.1
\end{aligned} \tag{E6}$$

E.2. Estimating changes in the number of trips by vehicle type

The congestion charge formula from equation (4) requires two sets of empirical objects that we do not estimate directly: (1) changes in the number of congestion zone crossings and outside trips, by vehicle type ($\frac{\partial t_g^c}{\partial \tau}, \frac{\partial t_b^c}{\partial \tau}, \frac{\partial t_g^o}{\partial \tau}, \frac{\partial t_b^o}{\partial \tau}$), and (2) changes in outside vehicle kilometers traveled ($\frac{\partial v^o}{\partial \tau}$) per trip. We describe below how we use our empirical estimates of changes in vehicle kilometers traveled to back out the implied changes in congestion zone trips and outside driving by vehicle type that resulted from Stockholm's congestion pricing policy.

Changes in number of congestion trips by vehicle type: To convert the estimates of changes in vehicle kilometers traveled for green and brown vehicles into changes in the number of congestion trips by vehicle type, we use the fact that the exemption of alternative fuel vehicles from Stockholm's congestion charge was removed in August 2012. Specifically, we assume that the effect of removing the alternative fuel vehicle exemption (τ_{-g}) on vehicle kilometers traveled in green and brown vehicles after 2012 mirrors the effect of the initial implementation of the congestion charge:

$$\frac{\partial KM_g}{\partial \tau_{-g}} := -\frac{\partial KM_g^c}{\partial \tau}, \quad \frac{\partial KM_b}{\partial \tau_{-g}} := -\frac{\partial KM_b^c}{\partial \tau}. \tag{E7}$$

To calculate the change in congestion zone trips taken in green vehicles, we combine the information on (a) the effect of removing the alternative fuel vehicle exemption on vehicle kilometers traveled (Table D1) and (b) what we inferred above about the average length of a cordon zone trip v^c :

$$\frac{\partial t_g^c}{\partial \tau_g} = -\frac{\partial KM_g}{\partial \tau_{-g}} \cdot \frac{1}{v^c} = \frac{93.3km}{17.5km} = 5.3 \tag{E8}$$

Then, we estimate the change in the number of non-congestion zone trips in green vehicles

by taking the difference between the change in all green congestion zone trips (Table 1, Panel B) less the change in green trips from equation (E8):

$$\frac{\partial t_g^o}{\partial \tau} = \frac{\partial t_g}{\partial \tau} - \frac{\partial t_g^c}{\partial \tau} = 5.6 - 5.3 = 0.3 \quad (\text{E9})$$

Similarly, to calculate the change in congestion zone trips made using brown vehicles, we combine the information on (a) the effect of removing the alternative fuel vehicle exemption on vehicle kilometers traveled (Table D1) and (b) what we inferred above about the length of non-cordon trips, v^o :

$$\frac{\partial t_b^c}{\partial \tau} = - \frac{\partial KM_b}{\partial \tau_{-g}} \cdot \frac{1}{v^c} = - \frac{211.8km}{17.5km} = -12.1 \quad (\text{E10})$$

Finally, we estimate the change in the number of non-congestion zone trips in brown vehicles by taking the difference between the change in all brown congestion zone trips (Table 1, Panel B) less the change in brown trips from equation (E10):

$$\frac{\partial t_b^o}{\partial \tau} = \frac{\partial t_b}{\partial \tau} - \frac{\partial t_b^c}{\partial \tau} = -14.0 + 12.1 = -1.9 \quad (\text{E11})$$

E.3. Changes in trip length for trips outside of the congestion zone

The total outside vehicle kilometers traveled per vehicle is equal to the product of the number of trips and the average trip length outside the congestion zone. Using data on per-vehicle total vehicle kilometers traveled (Table 1) and the average outside commuting distance v^o from the Swedish National Travel Survey (2007), we calculate the number of outside trips:

$$\begin{aligned} KM^o &= v^o \cdot t^o \\ t^o &= \frac{0.54 \cdot 15,299km}{19km} \approx 434.8 \end{aligned} \quad (\text{E12})$$

We then estimate the change in vehicle kilometers traveled per trip for trips outside the congestion zone. This is equal to the change in total vehicle kilometers traveled (Panel A, Table D1) less the change in kilometers traveled inside the congestion zone (Panel B, Table D1):

$$\begin{aligned}\frac{\partial KM}{\partial \tau} &= \frac{\partial KM^c}{\partial \tau} + \frac{\partial KM^o}{\partial \tau} \\ \frac{\partial KM^o}{\partial \tau} &= -153.5km + 118.6km \approx -34.9km\end{aligned}\tag{E13}$$

Finally, we estimate the change in the length of outside-zone trips ($\frac{\partial v^o}{\partial \tau}$) by taking the derivative of the total vehicle kilometers traveled outside the congestion zone with respect to the congestion charge:

$$\begin{aligned}\frac{\partial KM^o}{\partial \tau} &= \frac{\partial v^o}{\partial \tau} \cdot t^o + \frac{\partial t^o}{\partial \tau} \cdot v^o \\ \frac{\partial v^o}{\partial \tau} &= \frac{\frac{\partial KM^o}{\partial \tau} - \frac{\partial t^o}{\partial \tau} \cdot v^o}{t^o} \\ \frac{\partial v^o}{\partial \tau} &= \frac{-34.9 + 1.6 \cdot 19km}{434.8} \approx -0.01km\end{aligned}\tag{E14}$$

In calculating the change in outside trip distances, we use the number of outside trips t^o from equation (E12), the change in the vehicle kilometers traveled outside the congestion zone $\frac{\partial KM^o}{\partial \tau}$ from equation (E13) and the change in the number of outside trips $\frac{\partial t^o}{\partial \tau}$ (Table D1).

E.4. Emission externalities

To quantify the emission externalities, we combine the vehicle emission factors – the amount of a particular pollutant that a vehicle emits – with the social costs of each pollutant. Table E1 summarizes the vehicle emission factors and social costs of each pollutant.

We rely on a recent report by the European Environment Agency (2021) that provides vehicle emission factors for the main local (i.e., NH_3 , PM , SO_2) and global pollutants (i.e., CO_2) for petrol and diesel vehicles in Sweden. These pollution externalities have been shown to make up most of kilometer-weighted average emissions factors (Tarduno 2022). Although these emissions factors are based on a large number of assumptions concerning vehicle technology mix (e.g., the share of passenger cars), driving conditions (e.g., traveling speeds), and climatic conditions (e.g., temperature) (Zachariadis et al. 2001), we assume a constant emission factor for inside and outside the congestion zone. We use the fleet composition of Swedish petrol and diesel vehicles in 2006 to quantify the average local emissions rates per kilometer traveled.

As EVs produce no local emissions from tailpipes, we set the vehicle emission factors from Ammonia (NH_3) and Sulfur dioxide (SO_2) for green vehicles to zero. Following a recent report by the OECD (2020), we assume that non-exhaust particulate matter emissions for

fossil fuel cars are approximately equivalent to those of EVs. In addition, EVs charge from the electrical grid, which may generate emissions depending on the marginal fuel source (Holland et al. 2016). Based on the Swedish average electricity generation technology mix, the average carbon intensity for electricity used for charging equaled $29 \frac{g CO_2}{kWh}$ in 2020 ($348 \frac{g CO_2}{kg fuel}$ assuming an energy content of $12 \frac{kWh}{kg}$) (Morfeldt et al. 2021).

We convert these emissions rates into damages following a recent report by the European Environment Agency (2014) that provides costs of air pollution in Europe between 2008 and 2012 based on a value of a statistical life.²³ The report’s methodology quantifies the damage costs for the local pollutants following the European Commission’s DG Research (Holland et al. 1999; Bickel et al. 2005), which uses dispersion modeling in combination with estimates of pollution-mortality gradients to back out estimates of the damages from emitting a specific pollutant in a given location. To convert the carbon emission into a monetary equivalent, we use the Swedish carbon tax rate as an approximation for the social cost of carbon, which is currently set to SEK 1,190 ($\approx$ €105.2) per ton of CO_2 . We convert costs per kilogram of fuel into costs per liter by assuming that one liter of petrol equals 0.72 kilograms, i.e., petrol has a density of 0.72 kg per liter. Finally, we express the costs per kilometer based on the average fuel efficiency of fossil fuel vehicles ($8.37 \frac{l}{100km}$).

Table E1: Social costs of pollutants

Pollutant	Emission factors [$\frac{g}{kg fuel}$]	Social cost of pollutant [$\frac{€}{kg}$]	Costs per liter [$\frac{€}{l}$]	Costs per km [$\frac{€}{km}$]
<i>A. Brown Vehicle</i>				
Emission externalities				
Fine particulate matter ($PM_{2.5}$)	0.31	23.2	0.005	0.0004
Particulate matter (PM_{10})	0.31	15.01	0.003	0.0003
Ammonia (NH_3)	11.14	12.15	0.097	0.0082
Sulfur dioxide (SO_2)	8.19	15.44	0.091	0.0076
Carbon dioxide (CO_2)	3,870	0.105	0.293	0.0245
			0.489	0.041
<i>B. Green Vehicle</i>				
Fine particulate matter ($PM_{2.5}$)	0.31	23.2	0.005	0.0004
Particulate matter (PM_{10})	0.31	15.01	0.003	0.0003
Carbon dioxide (CO_2)	348	0.105	0.026	0.0022
			0.034	0.0029

Notes: This table reports the vehicle emission factors and social costs of each pollutant for brown (Panel A) and green vehicles (Panel B). All externalities are expressed in real 2021 €.

23. The European Environment Agency reports a “high” and “low” value for each pollutant. We take the mean of these two values.

E.5. Congestion externalities

To assign congestion externalities to trips, we follow the External Costs of Transport study (2011), which provides external congestion costs in European cities. They assign mean values to typical traffic situations to indicate the magnitude and variability of marginal congestion costs. The main driving factors of marginal congestion costs are speed-flow relationships, road vehicle capacity demand, the value of travel time, the occupancy of vehicles in terms of passengers and tons of freight (Maibach et al. 2008). To determine congestion externalities, we refer to the estimates (measured in 2008 €) in Table 38 of the External Costs of Transport study (2011). Specifically, we use the estimates for small and medium urban areas for the congestion externalities within the cordon zone and rural areas for the congestion externalities outside the congestion zone. The congestion costs in small and medium urban areas (< 2,000,000 citizens) are €0.38 per kilometer and €0.13 per kilometer in rural areas. Based on an average congestion and non-congestion zone journey length of 17.5km and 19km, respectively, we estimate a congestion externality of approximately €6.65 and €2.47 per trip, which exceeds the peak-hour congestion pricing in Stockholm.

E.6. Evaluating equation 5

Plugging in our coefficient estimates and our off-the-shelf externality parameters (which are summarized in Table 2), and accounting for differences in units between our per-person estimates and several per-vehicle formula inputs, we recover our optimal charge estimate.

Equation (5) is:

$$\begin{aligned}
 \tau = & \underbrace{(\phi_b + \gamma_b)}_{\text{Damages per taxed trip}} + \underbrace{\Delta N_g(\widetilde{\phi}_g + \widetilde{\gamma}_g) + \Delta N_b(\widetilde{\phi}_b + \widetilde{\gamma}_b)}_{\Delta \text{Fleet composition}} \\
 & + \underbrace{\Delta T_g^c(\overline{\phi}_g^c + \overline{\gamma}_g^c) + \Delta T_g^o(\overline{\phi}_g^o + \overline{\gamma}_g^o) + \Delta T_b^o(\overline{\phi}_b^o + \overline{\gamma}_b^o)}_{\Delta \text{Non-taxed trips}} \\
 & + \underbrace{\Delta V^c(\hat{\phi}^c + \hat{\gamma}^c) + \Delta V^o(\hat{\phi}^o + \hat{\gamma}^o)}_{\Delta \text{Commute distances}}.
 \end{aligned}$$

The externality terms for this expression are:

Parameter	Derivation	Value
$\widetilde{\phi}_g + \widetilde{\gamma}_g$	$(17.5 \times 2.5 + 19 \times 2.7) \times 0 + 17.5 \times 2.5 \times 0.38 + 19 \times 2.7 \times 0.13$	23.29
$\widetilde{\phi}_b + \widetilde{\gamma}_b$	$19 \times 432.1 \times 0.04 + 19 \times 432.1 \times 0.13$	1395.7
$\overline{\phi}_g^c + \overline{\gamma}_g^c$	$0.007 \times 17.5 \times (0 + 0.38)$	0.047
$\overline{\phi}_g^o + \overline{\gamma}_g^o$	$0.007 \times 19 \times (0 + 0.13)$	0.017
$\overline{\phi}_b^o + \overline{\gamma}_b^o$	$1.138 \times 19 \times (0.04 + 0.13)$	3.68
$\hat{\phi}^c + \hat{\gamma}^c$	$1.138 \times 399.6 \times 0.04 + (1.138 \times 399.6 + 0.007 \times 2.5) \times 0.38$	191.1
$\hat{\phi}^o + \hat{\gamma}^o$	$1.138 \times 432.1 \times 0.04 + (1.138 \times 432.1 + 0.007 \times 2.7) \times 0.13$	83.6

Finally, the denominator of all substitution terms, $\Delta n_b t_b^c + \Delta t_b^c n_b$, evaluates to $(0.0084)(399.6) + (12.1)(1.138) = 17.13$. Plugging in the remaining policy responses, we have:

$$\begin{aligned}
\tau &= \underbrace{17.5 \times (0.04 + 0.38)}_{\text{Damages per taxed trip}} \\
&+ \underbrace{\frac{0.0052 \times 1.138}{-17.13} \times 23.29 + \frac{(-0.0084) \times 1.138}{-17.13} \times 1395.7}_{\Delta \text{ Fleet composition}} \\
&+ \underbrace{\frac{5.3 \times 1.138}{-17.13} \times 0.047 + \frac{0.3 \times 1.138}{-17.13} \times 0.017 + \frac{(-1.9) \times 1.138}{-17.13} \times 3.68}_{\Delta \text{ Non-taxed trips}} \\
&+ \underbrace{\frac{(-0.116) \times 1.138}{-17.13} \times 191.1 + \frac{(-0.01) \times 1.138}{-17.13} \times 83.6}_{\Delta \text{ Commute distances}} \\
&= \underbrace{7.35}_{\text{direct}} + \underbrace{(-0.008 + 0.779)}_{\text{fleet}} + \underbrace{(-0.016 - 0.000 + 0.464)}_{\text{non-taxed trips}} + \underbrace{(1.473 + 0.056)}_{\text{commute}} \\
&= \mathbf{10.09} \tag{E15}
\end{aligned}$$

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